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Occupant Behaviour with regard to Control of the Indoor Environment

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OCCUPANT BEHAVIOUR WITH REGARD TO CONTROL OF THE INDOOR ENVIRONMENT

Ph.D. Thesis

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PREFACE

This PhD thesis describes the work carried out by the author at the Technical University of Denmark, International Centre for Indoor Environment and Energy, Department of Civil Engineering, Lyngby, Denmark from August 2005 to March 2009. Supervisors during the PhD study were Professor and Director PhD Bjarne W. Olesen and Associate Professor, PhD Jørn Toftum, both from ICIEE, DTU.

I would like to thank my two supervisors for their support and cooperation in the project. I really appreciate the help I have received from Bjarne who has pointed me in the right direction and supported my decisions all the way. He was always able to find time in his busy schedule for constructive discussions of how to proceed.

I would also like to express my sincere gratitude to Jørn who was always ready with quick and constructive response. The quality of the project would not have been the same without his numerous and excellent comments to the material I presented to him.

I appreciate the fruitful cooperation I have had with Klaus Kaae Andersen, who has contributed significantly to the statistical quality of the work. The statistical approaches and analytic work would not have been possible without his help.

The work was financially supported by the companies Danfoss, Velux and WindowMaster. In the beginning of the project a support group with participants from the supporting companies was formed. I would like to thank Niels Gregersen, Steen Hagelkær, Karsten Duer, Jens Møller Jensen, and Hardy Jepsen for their time and interest in the project. Their comments and remarks were always an inspiration to me. I would like to thank the supporting companies for giving me the opportunity to conduct research in this interesting field.

I would like to thank my colleagues and friends at the International Centre for Indoor Environment and Energy. I have always enjoyed the special international atmosphere at the centre. I feel privileged to know some of the best scientists in the world in field of the indoor climate.

Finally I would like to dedicate the work to Kitt and our two children Gro and Hjalte. Kitt has always supported me and has given me the time and space to pursue my ambitions and goals, even though it sometimes resulted in sacrifices in our family.

SUMMARY

A large proportion of the world's energy consumption is spent in an effort to maintain a comfortable and healthy indoor environment. As a consequence reductions in the energy consumed to climatise buildings are instrumental to the efforts of reducing energy related CO_2 emissions and alleviating the European energy import dependencies.

Whole building simulations of indoor environment and energy consumption are becoming more and more used in the design phase of buildings. Previously the simulation of physical factors such as transmission and ventilation heat losses has received a lot of attention. As a consequence, most programs are capable of accurate simulations of the physical properties of a building. However, even though the occupants' control of the various systems in the building has a significant impact on the energy consumption and the indoor environment, only few studies have focused on the behaviour of their occupants. As a consequence, there is a need to investigate occupants' interactions with building controls, such as opening of windows, adjustments of heating set-points, use of solar shading, etc. Some models of occupants' interactions with operable windows do exist, but these are based on measurements in offices, and they only take thermal comfort into account.

The work described in this thesis mainly focused on the window opening and heating behaviour of occupants in Danish dwellings. Also the use of solar shading and artificial lighting has received some attention.

The control related behaviour of occupants was found to have a substantial impact on the energy performance of a building. This becomes increasingly important in buildings designed using the adaptive model of thermal comfort, where occupants are encouraged to interact with building controls. It was found that determination of acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of the occupants.

Large differences in the behaviour patterns of occupants were found between dwellings. The time of day had a great effect on the behaviour patterns in the investigated dwellings. This effect was significant at similar environmental conditions, suggesting that environmental variables alone can not explain all the variance in the observed behaviour. The results showed that the behaviour of the occupants was driven by a variety of variables, including thermal comfort, perception of air quality and other IEQ variables, weather and physical aspects of the dwelling.

Based on observation of real behaviour, a definition of occupant behaviour patterns in building simulation programs was proposed. The proposed model was implemented into

the simulation environment IDA ICE and compared to a reference simulation, which emulated a simulation as it could have been performed by a designer. There were large differences in the simulated indoor environment between the two simulations, which resulted in considerably lower energy consumption in the reference simulation. Since the definition is based on observation of real behaviour, it will significantly increase the validity of the simulation result and ensure that the results are closer to reality, when implemented into simulation programs. Furthermore, it will enable designers to better assess the effects of the occupant's behaviour and thereby the effects of different designs.

RESUMÉ

En stor del af verdens energiforbrug bliver brugt i en bestræbelse på at fastholde et komfortabelt og sundt indeklima. Som en konsekvens er reduktioner i energiforbruget til at klimatisere bygninger en medvirkende faktor i indsatsen for at reducere den energirelaterede CO_2 udledning og afhjælpe den europæiske energiimportafhængighed.

Simuleringer af indeklima og energiforbrug bliver i stigende grad brugt i projekteringsfasen af bygninger. Tidligere har simulering af fysiske faktorer såsom transmissions- og ventilationsvarmetab fået megen opmærksomhed. Som følge heraf er de fleste programmer i stand til at udføre præcise simuleringer af de fysiske egenskaber af en bygning. Men selv om brugernes kontrol af forskellige systemer i bygningen har en betydelig indvirkning på energiforbruget og indeklimaet, har kun få undersøgelser fokuseret på brugernes adfærd. Som en konsekvens heraf er der et behov for at undersøge brugernes interaktioner med bygningers systemer, såsom åbning af vinduer, justeringer af termostaters indstilling, brug af solafskærmning osv. Der findes nogle modeller af brugeres interaktioner med betjenbare vinduer, men disse er baseret på målinger i kontorer og tager kun termisk komfort i betragtning.

Arbejdet, der er beskrevet i denne afhandling, har primært fokuseret på brugernes vinduesåbnings- og opvarmningsadfærd i danske boliger. Også brugen af solafskærmning og kunstig belysning har modtaget en vis opmærksomhed.

Af afhandlingen fremgår det, at brugernes kontrolrelaterede adfærd havde en væsentlig indflydelse på en bygnings energimæssige ydeevne. Denne indflydelse er vigtigere i bygninger konstrueret ved hjælp af den adaptive model for termisk komfort, hvor brugerne opfordres til at interagere med bygningens systemer. Det blev konstateret, at fastsættelsen af acceptable termiske betingelser med den adaptive model kan resultere i betydelige energibesparelser, og samtidig vil det ikke have store konsekvenser for brugernes mentale ydeevne.

Adfærdsmønstrene i forskellige boliger adskilte sig kraftigt fra hinanden. Tidspunktet på dagen havde en stor effekt på adfærdsmønstrene i de undersøgte boliger. Denne effekt var signifikant ved ens miljømæssige forhold, hvilket tyder på, at miljøvariabler ikke alene kan forklare hele variansen i den observerede opførsel. Resultaterne viste, at beboernes adfærd blev drevet af en række variabler, herunder termisk komfort, opfattelsen af luftkvalitet og andre IEQ variabler, vejr og fysiske aspekter af boligen.

Baseret på observation af adfærd blev en definition af brugeradfærdsmønstre i simuleringsprogrammer foreslået. Den foreslåede model blev implementeret i simuleringsprogrammet IDA ICE og sammenlignet med en referencesimulering, som efterlignede en simulering, som den kunne have været udført af en rådgiver. Der var

store forskelle på det simulerede indeklima i de to simuleringer, hvilket resulterede i betydeligt lavere energiforbrug i referencesimulering. Da definitionen er baseret på observation af virkelig adfærd, vil det forøge gyldigheden af simuleringer betydeligt og sikre, at resultaterne er tættere på virkeligheden, hvis den implementeres i simuleringsprogrammer. Det vil desuden give rådgivere en bedre mulighed for at kunne vurdere virkningerne af en persons adfærd og dermed virkningerne af forskellige udformninger.

LIST OF PAPERS

PAPER I – Andersen RV, Toftum J, Andersen KK and Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings, Energy and Buildings 41 (2009) 11–16

PAPER II – Andersen RV, Toftum J and Olesen BW. Long term monitoring of occupant behaviour and indoor environment in Danish dwellings, Submitted to Building and Environment

PAPER III – Toftum J, Andersen RV and Jensen KL. Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions, Building and Environment, in press, DOI: 10.1016/j.buildenv.2009.02.007

PAPER IV – Andersen RV, Olesen BW and Toftum J. Simulation of the Effects of Occupant Behaviour on Indoor Climate and Energy Consumption, Proceedings of Clima 2007: 9th REHVA world congress: WellBeing Indoors, Helsinki, Finland, 2007

1 INTRODUCTION

Buildings account for more than 40 % of the primary energy consumption in the EU member states, and households are responsible for the consumption of more than 26 % [EC, European Union Energy and Transport in Figures]. In the USA buildings' share of consumption of primary energy has been increasing from 34 % in 1980 to 40 % in 2005. More than 66 % of that consumption is used for heating, ventilation, air conditioning and lighting. As a result more that 26 % of the total primary energy consumed in the USA is used in an effort of maintaining a healthy and comfortable indoor climate [Building energy data book (2007)]. In 2005 the USA and EU member states were responsible for 37 % of the global energy related CO_2 emissions [European Environment Agency]. This implies that reduction of the energy consumed to condition the indoor environment is instrumental to the efforts of reducing the global CO_2 emissions.

The energy performance of a building is significantly influenced by the user behaviour like the setting of room thermostats and opening of windows. In the design process of a building it is common to use whole building simulations to determine the performance of the building and the effects of changes to the design. As Soebarto and Williamson (2001) point out it is now indisputable that using simulation to establish the life-cycle performance of a proposed building in its various aspects is the current 'best practice'. Most building simulation programs provide possibilities of regulating the simulated environment by adjusting the building control systems (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to very large off-set between simulation results and actual energy use [Macintosh and Steemers (2005), Bishop and Frey (1985)]. In fact the behaviour of the occupants affects the energy performance of a building to a much larger degree than the thermal processes within the façade [Hoes et al. (2009)]. As building regulations call for lower energy consumption the insulation level and tightness of buildings increase. Consequently the occupants will have larger effects on the air change rate in the building resulting in an increased influence of occupant behaviour on the energy consumption and indoor environment. This implies that designers' inclusion of occupants' interactions with the building controls becomes increasingly important.

Some designers use a strategy of controlling the most important features centrally in an effort of minimizing the influence of occupant behaviour on the performance of the building. But occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer from fewer building related symptoms than occupants who are exposed to environments of which they have no control [Leman and Bordass (1999), Paciuk (1989), Toftum (2009), Brager et al. (2004)]. These studies underline the importance of providing occupants with the opportunity to control the indoor environment. However, doing so increases the difficulty in predicting the performance of the building. If the occupants have the possibility to manipulate the temperature set-points, ventilation rates etc., the performance of the building is affected by the behaviour of the occupants who might not optimally use the controls. One challenge is that occupant behaviour varies significantly from one person to another. In effect, this variation in occupant behaviour results in large variations in the energy consumption of buildings.

Two important parameters influencing energy consumption in buildings are indoor temperature and air change rate. In Danish dwellings mechanical cooling is almost never used, which means that the indoor temperature depends on the heating set-point in winter and on the air change rate in the summer. As a consequence, window opening behaviour and heating set-point behaviour of occupants play an important role in determining the energy consumption and indoor environment of a household.

The aim of the present PhD project was to define behaviour patterns based on the quantification of real occupant behaviour. The main focus was window opening behaviour and heating behaviour but also electrical lighting and solar shading were investigated. In the beginning of the project a simulation study was conducted to estimate the extent of the influence of occupant behaviour on the energy consumption in buildings. This study was reported in paper IV.

A questionnaire survey was conducted to quantify the relationships between environmental physical and demographic variables and the behaviour of occupants in dwellings. This part of the study was reported in paper I. The second aim of the study was to investigate driving forces for the behaviour of the occupants. This part of the study was reported in conference papers, which have not been included as papers in this thesis. Instead most findings are presented and discussed in section 5.

Long term measurements of occupant behaviour and environmental variables were carried out in 15 dwellings. Based on these measurements a model of occupant interactions with operable windows and heating thermostats was reported in paper II. This model was implemented in a simulation program and the effects on energy consumption and indoor environment was estimated by comparison to a reference simulation. The implementation of the proposed model is described in section 7.

Finally, the effects of applying the adaptive model of thermal comfort on the productivity of office occupants was investigated in a simulation study reported in paper III.

2 OBJECTIVES

The purpose of the project described in this thesis was to investigate occupants' interactions with building controls with special focus on control of the indoor air quality and thermal comfort. A key objective was to identify variables with influence on occupants' behaviour and to quantify this influence.

This was done partly by a questionnaire study and partly by measurements in a number of dwellings during a winter and summer season.

Another objective was to evaluate the influence on energy performance of assumed occupant behaviour by dynamic computer simulation and define a model of realistic behaviour patterns that can be implemented in building simulation tools.

The specific objectives of the studies reported in the papers included have been to:

Paper I. Identify factors that have an influence on the behaviour of occupants in Danish dwellings.

Paper II. Quantify the influence of environmental factors on occupant behaviour in Danish dwellings

Paper III. Investigate the effects of applying the adaptive model of thermal comfort on the productivity of office occupants

Paper IV. Assess the impact of energy consuming and energy efficient behavioural patterns on the energy performance of a building

3 BACKGROUND

The topic of occupant behaviour with regard to control of the indoor environment has previously been studied with two aims: Investigating the window opening and ventilation behaviour to find if occupants are provided with adequate fresh air, and energy related investigations of occupant behaviour. The former category of studies has usually been carried out in dwellings and has a health or a comfort perspective, while the latter category has mostly been studied in offices with a comfort, energy and performance perspective. Even though dwellings are responsible for consuming more than ¼ of the total primary energy in the EU member states [EC, European Union Energy and Transport in Figures], the studies that are aiming at implementing realistic behaviour patterns in simulation programs have been based on occupant behaviour in offices [Haldi and Robinson (2008), Rijal et al. (2007), Herkel et al. (2005)]. As a result, the main focus of the PhD project presented in this thesis has been on investigations of behaviour in dwellings with an energy perspective.

3.1 Adaptive opportunities

The adaptive principle as described by Nicol and Humphreys (2002) states that: “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort”. These actions can be divided into changes that alter the environment to make it more comfortable and into changes that adapt the occupant to the prevailing environment. The first might be to adjust the heating set-point, to open/close a window, to turn lights on or off or to adjust the solar shading, while adjusting clothing, adjusting body posture and consuming hot or cold drinks fall into the latter category. Since the first category affects the energy consumption directly, the main focus of the current project has been on this category of actions. Specifically the studies have investigated window opening behaviour and the control of heating and to smaller degree the control of shading devices and artificial lighting. Since thermal comfort is thought to be one of the main drivers of many of the adaptive actions that affect the consumption of energy directly, clothing behaviour has also been investigated, but only by reviewing literature.

3.1.1 Window opening behaviour

Many investigations of air change rates and window opening behaviour have found strong seasonal effects. Already in 1951 Dick and Thomas (1951) looked at occupants’ interaction with building controls. They found that external temperature alone accounted for more than 70% of the variation in the number of open vents and windows. Additionally 10% of the observed variance could be attributed to wind speed. In 1977 Brundrett (1977) studied 123 dwellings and found that weather explained between 64%

and 68% of the variance in the number of open windows. Also Wallace et al. (2002) noted a strong seasonal effect on the fraction of time the window was open.

Recently, the effect of indoor and outdoor temperature on the window opening behaviour in offices was investigated by means of logistic regression [Rijal et al. (2007), Haldi and Robinson (2008), Herkel et al. (2008), Yun and Steemers (2008), Yun et al. (2008)]. The general trend has been to infer the probability of the window state as a function of indoor and outdoor temperature, while some have investigated the probability of opening a window (change from one state to another) as a function of indoor temperature [Yun and Steemers (2008), Yun et al. (2008)]. The problem in relating the state of the window to explanatory variables is that the method provides inadequate data for simulation purposes. In a simulation case the method might be used to provide information on how many windows are open in a specific time-step. In the next time-step that number might change or it might not change. The problem is that the method does not stipulate what happens to the individual window when it is opened. Without such stipulations there will be no relationship between the previous and the current state of the individual window. As a consequence the method might lead to the illogical result that some windows might stay open for days or weeks while others open and close at each time-step. One of the purposes of paper II was to attempt to determine relations between monitored indoor and outdoor climate variables and the probability of opening or closing the window (change from one state to the other). As described in paper II and in section 7.1 in this thesis, this provided a relationship between the previous and the current state of the window for simulation purposes.

3.1.1.1 Effects of window opening behaviour on air change rates

One parameter with a high influence on the energy consumption in dwellings is the air change rate. The air change rate is affected by the occupants' behaviour, indoor environment and weather, but how dependent is the air change rate on the behaviour of the occupants? The answer to that question was not studied directly, but investigated by reviewing literature.

As early as 1943 Bedford et al. (1943) conducted 358 measurements of the air change rate in various houses in London using the decay of coal-gas liberated into the air. They discussed the effects of flues, air gratings, cracks and leakages on the air change rate in the houses and finally noted that any reasonable amount of ventilation could be obtained if liberal window openings were provided. They obtained as many as 30 air changes per hour by means of cross-ventilation in experimental rooms. Since then, houses have been tightened and sealed, increasing the relative effect of window opening on the air change rate. In fact, when Wallace et al. (2002) measured air change rates in a house in Virginia during a year, they found that the window opening behaviour had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. In another paper describing the same measurements Howard-Reed et al. (2002) stated that opening of a single window increased the air change rate by an amount roughly proportional to the width of the opening, reaching increments as high as 1.3 h^{-1}. Multiple window openings increased the air change rate by amounts ranging from 0.10 to 2.8 h^{-1}.

Bedford et al. (1943), Wallace et al. (2002), Howard-Reed et al. (2002) and Offerman et al. (2008) focused on the exposure to contaminants at low air change rates. While Bedford et al. (1943) found an average air change rate of 0.8 h^{-1} and with only 11 % of the measurements under 0.4 h^{-1} in London, Offerman et al. (2008) found that 75 % of homes without mechanical ventilation had air change rates lower than 0.35 h^{-1}, suggesting that homes had been tightened to such an extent that occupants needed to actively adjust building controls to obtain adequate supply of fresh air. Also, Price and Sherman (2006) found that, depending on season, between 50 % and 90% of Californian homes had air change rates lower than 0.35 h^{-1}. The results of Offerman et al. (2008) and Price and Sherman (2006) suggest that many houses in California are under-ventilated according to local standard recommendations because ventilation systems are too small and because the occupants do not operate the windows adequately. This was especially evident in the winter months implying that the occupants opened windows to a smaller degree in winter than in summer.

According to Keiding et al. (2003) who conducted a questionnaire survey in Danish Dwellings, 53.1 % slept with an open window during autumn while 25.2 % had a window open during the night in winter time, which in most situations should ensure an air change rate of more than 0.35 h^{-1}. They found that 91.5 % of the respondents vented by opening one or more windows each day throughout the year. The results showed that a large proportion of Danish occupants use windows to adjust the supply of fresh air to the dwelling. The effects of this behaviour on the energy consumption might be substantial. One of the main objectives of this PhD project was to investigate the window opening behaviour and the effects it had on energy consumption.

Kvistgaard et al. (1985) measured air change rate and temperature in 16 Danish dwellings and found an average air change rate of 0.68 h^{-1}. In a later paper Kvistgaard and Collet (1990) noted that there was considerable difference in the total air change between the individual dwellings. As the basic air change[1] was fairly similar, it was concluded that it was the behaviour of the occupants that caused these large differences.

[1] With all windows and doors closed

The studies mentioned above show that air change rates vary significantly from home to home and the window opening behaviour of the occupants has a considerable effect on the air change rate. Since the air change rate has a big impact on the energy consumption it is evident that different behaviour patterns will result in different energy consumptions. One aspect that affects the air change rate is how often and for how long the windows are opened but also the degree of opening will have an impact.

3.1.1.2 Degree of opening

While most studies have investigated the number of open windows and the probability of opening a window, only few have examined the degree of opening. Fritch et al. (1990) measured the opening angle of four windows in four offices every half hour during the heating seasons of 1983-1984 and 1984-1985. Monitored variables included indoor and outdoor temperature, wind speed and solar radiation impinging on the window. The data analysis ruled out the wind speed and solar radiation as significant drivers for determining the angle of opening. The indoor temperature was discarded as the indoor temperature was relatively constant and due to the fact that it dropped when the supply of fresh air was increased as a consequence of opening the window[2]. This left the outdoor temperature as the only significant variable in the determination of the window angle.

Fritch et al. (1990) found that windows were usually left in the same position for long periods of time which is consistent with the findings of Herkel et al. (2005). They monitored the status of 34 large and small windows in an office building and were able to determine if the large windows were completely open or tilted open. They found that large windows that were opened completely remained open for a short time, while large windows that were tilted open and small open windows usually remained open for the entire day.

In paper II the angle of three windows was measured and analysed to find relations to other monitored variables.

3.1.1.3 Drivers for window opening behaviour

Haldi and Robinson (2008) argued that indoor temperature would be better a predictor of window opening behaviour than the outdoor temperature because indoor temperature is a driver for opening and closing windows to a much larger extent than outdoor temperature. However, the indoor temperature is affected by the windows’ degree of opening, which makes the analysis of window state based on indoor temperature difficult to interpret. The problem is that the predictive variable is influenced by the state that it is trying to predict. In a cold climate the low indoor temperatures would occur

[2] This was problematic since the predictive variable was influenced by the state it was trying to predict.

when the windows are open and not when they are closed. In such a case the result of the analysis would be that the inferred probability of a window being open increases with decreasing indoor temperature, with the illogical implication that the probability of opening a window would increase with decreasing indoor temperatures.

Another problem with this approach is that the driving forces for opening and closing a window might be different. The window might be opened due to poor IAQ and closed because of low indoor temperature. In paper II these two problems were overcome by analysing the data to infer the probability of opening or closing a window – that is a change from one state to the other, rather than the probability of the window state itself.

Most recent studies have been limited to the investigation of thermal stimuli [Rijal et al. (2007), Haldi and Robinson (2008), Herkel et al. (2008), Yun and Steemers (2008)] although other studies have found that other drivers such as indoor air quality, noise, rain etc. also play an important role in determining the window opening behaviour [Johnson and Long (2005), Warren and Parkins (1984)]. One of the purposes of the studies reported in paper I and paper II was to investigate the effect of other than thermal variables on the window opening behaviour.

3.1.2 Heating set-point

Weihl and Gladhart (1990) monitored the behaviour of occupants in seventeen households in 1983-1985 and 1986-1987. They observed at least five thermostat set-point behaviour patterns and found that in each household the thermostat set-point behaviour was remarkably steady from year to year.

Xu et al. (2009) conducted a questionnaire survey and field observations in China to study how occupants adjusted thermostatic radiator valves (TRVs). They also found that occupants could be divided into groups depending on their behavioural patterns regarding the TRV set-point. 26 % of the occupants never changed the set-point. 46 % of the occupants only seldom adjusted the TRV set-point, which remained unchanged sometimes up to several months. The remaining 28 % of the occupants regulated the TRVs frequently, sometimes several times a day. The studies mentioned above indicate that there are large differences in the use of thermostats and that these differences are the results of different habits among occupants.

Karjalainen (2007) investigated gender differences in the adjustment of thermostat set-point by means of a questionnaire survey and a controlled experiment. He found significant differences between the genders in thermal comfort and in the use of thermostats. Females were less satisfied with room temperatures than males and preferred a higher heating set-point than males, but males adjusted the thermostat set-point more often than females did. In another paper, Karjalainen (2007) interviewed 27 office occupants in 13 buildings about the use of room thermostats and found a range of misunderstandings which would all lead to incorrect use of the thermostat. While these misunderstandings were connected to room thermostats, many of them could be transferred to TRVs and result in the same incorrect use patterns. The results of Karjalainen confirmed the findings of Rathouse and Young (2004) who conducted six focus group interviews on the use of heating controls in the UK. They found that many focus group participants did not understand how to use the thermostats (this applied to both the room thermostats and the TRVs). There was a great variation in the use of both room thermostats and TRVs, ranging from no adjustments at all to frequent adjustments. Furthermore, a great variation was found in the reported preferable temperature of the focus group participants.

Peeters et al. (2008) conducted two surveys in dwellings in Belgium and found that the majority of occupants did not know how to operate the TRVs. As a result, overheating often occurred. It should however be noted that heating systems in Belgium mostly rely on room thermostats and TRVs. In Denmark the most common control principle is to use external weather compensation in the control of supply water temperature and TRVs to control the flow of water through the heaters. The above mentioned investigations of occupants' interactions with heating controls indicate that temperature set-points are controlled by habits and that misperceptions of thermostats are widespread. The studies show that there are large differences in the frequency of set-point adjustments between occupants which could lead to differences in the energy consumption in the building. When designers calculate the energy consumption of a building they often assume that the heating set-point is constantly 20 °C. The studies mentioned above all show that the set-point temperature is adjusted by occupants – sometimes on a daily basis. As a consequence, using an assumed constant set-point temperature in the calculations will result in wrong outcomes. One of the aims of this PhD project was to investigate the temperature set-point behaviour so that the results of the investigations might facilitate more realistic outcomes of building simulations.

3.1.3 Clothing adjustment

Newsham (1997) conducted a simulation study to investigate the effects of clothing adjustments on the energy consumption of buildings. He found that if clothing insulation was adjusted vividly, heating set-points could be lowered and cooling set-points could be increased resulting in energy savings of up to 41%. However, the results of Baker and Standeven (1994) suggest that clothing insulation is not adjusted vividly. They conducted a survey in seven buildings in Athens and Lyon and asked the occupants if they had made clothing adjustments within the last hour. This was only answered in the affirmative 62 times out of 864 observed hours. This resulted in a comment by Baker and Standeven (1996) that occupants made a negligible number of alterations to their clothing ensemble on an hourly basis, suggesting that clothing was not used to improve comfort on this timescale. However, a question in the morning asking whether thermal conditions had affected the choice of clothes for the day, suggested that for 75 % of times this had been a factor. There is no doubt that clothing adjustments have a large impact on the energy consumption, but as the result of Baker and Standeven suggest occupants only rarely alter their clothing during the day. As a result energy savings of 41% are probably not achievable without compromising thermal comfort.

In another study by Morgan and de Dear (2003), it was reported that clothing worn in a shopping mall in Sydney was determined by the outdoor temperature. The study showed that the clothing insulation level depended exponentially on the past weather. The half-life of this exponential decay was about 2 days. If the weather forecast was taken into consideration as well as the past weather, 59 % of the day to day variance in clothing insulation was accounted for. Markee White (1986) carried out a field study in a 17 story office building. She found that the anticipated outdoor environmental conditions influenced the choice of clothing worn on a specific day more than the anticipated indoor office temperature did. These two studies suggest that the outdoor temperature has a very high impact on the choice of clothing. This was further investigated by De Carli et al. (2007) who analysed the relationship between clothing behaviour and the indoor and outdoor temperature based on field investigations in 28 cities all over the world. They found that the outdoor temperature at 6 o'clock in the morning influenced the clothing insulation the most. The influence was larger in naturally ventilated buildings than in mechanically ventilated buildings. In contradiction to the results of Morgan and De Dear (2003), but in agreement with Markee White (1986), De Carli et al. (2007) did not find an influence of gender on the clothing behaviour. Since thermal comfort is thought to be one of the main determinants of temperature set-point and might have a big impact on the window opening behaviour, clothing behaviour will also influence these parameters. Consequently the occupants' choice of clothing will affect the energy performance of a building. However, clothing behaviour is a means of adapting the occupant to the indoor environment and as such does not affect energy consumption directly. Some of the findings mentioned above have been used in the simulation studies described in this thesis. However, since the main focus of the PhD project was to investigate adaptive behaviour with a direct influence on energy consumption, the clothing behaviour was not investigated.

3.1.4 The adaptive model of thermal comfort

The adaptive model of thermal comfort proposed by de Dear and Brager (1998) and included in recent versions of ASHRAE standard 55 and EN 15251 is a regression equation that relates the acceptable minimum and maximum indoor temperature to the monthly average outdoor temperature. In EN 15251 (2007) the relation is as presented in figure 1. This model can be used in buildings without mechanical cooling and easy access to operable windows. It is based on the notion that the occupants’ level of adaptation and expectation is strongly related to outdoor climatic conditions.

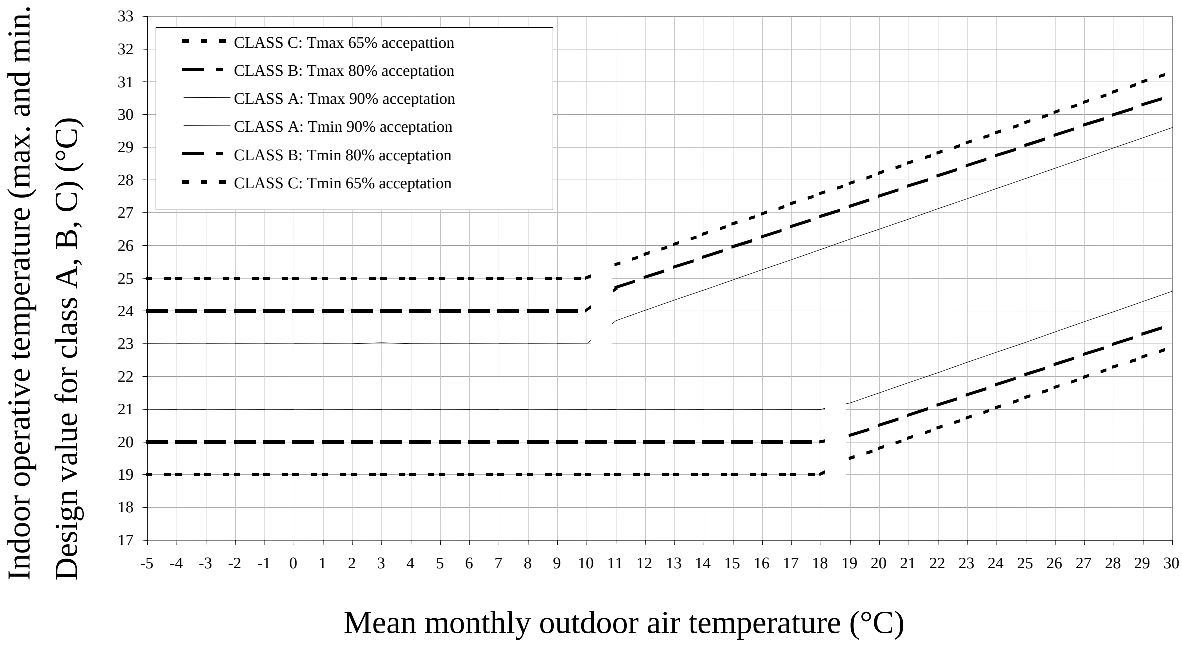

Figure 1: Minimum and maximum design values for the indoor operative temperature according to EN 15251(2007)

Hoes et al. (2009) conducted a simulation study on the effects of occupant behaviour on the simulated energy performance of buildings and concluded that the simple approach used nowadays for design assessments applying numerical tools are inadequate for buildings that have close interactions with the occupants. When using the adaptive model in the design of a building, occupants are expected to adapt to the environment or adapt the environment to their needs. This means that in such buildings occupants are expected to closely interact with the available building controls. As a consequence, the behaviour of the occupants becomes increasingly important in the determination of the indoor environment in and the energy performance of the building.

In warm climates, the adaptive model might lead to more relaxed temperature criteria than when using more conventional methods such as the PMV model, which might lead to lower energy consumption. However, the adaptive model does not take the occupants’ productivity into account. As a consequence application of the adaptive model might lead to productivity loses which can have significant economic implications. The implications of application of the adaptive model on the productivity of office occupants were examined in paper IV.

3.2 The effect of occupant behaviour on energy consumption in buildings

The following section describes studies that have investigated the influence of occupant behaviour on energy performance of buildings.

Seligman et al. (1977/78) investigated energy consumption in 28 identical town houses and found the largest variation in energy consumption to be two to one. Furthermore, the energy consumption of the houses depended on the occupants. Sonderegger (1977/78) measured gas consumption used for heating in 205 town houses located in the same group of houses as the study of Seligman et al. (1977/78). They found the highest consumption to be more than three times as high as the lowest consumption. 54 % of the variance in gas consumption was explained by design features of the houses, such as number of rooms, area of windows etc. which left 46 % of the variance unexplained by the design features. By comparing changes in gas consumption between two heating seasons of occupants who moved into the houses with that of occupants who stayed in the houses, they concluded that 71 % of the unexplained variance was due to occupant related consumption patterns.

In a recent study, Maier et al. (2009) measured energy consumption in 22 houses in Germany over a two year period. Apart from the ventilation principle, the houses were identical. They found the largest difference in energy consumption between 12 of the houses that were ventilated identically to be 284%. The house with the lowest consumption of energy had the lowest average temperature implying that the occupants conserved energy by having a lower heating set-point in the heating season.

Garland et al. (1993) monitored energy consumption in four houses of identical layout in Washington from 1987 to 1992. They found that changes in heating set-point patterns accounted for as much as 27 % of the total energy used for heating, while variations in the door and window opening behaviour accounted for up to 17 %. The houses had a monthly average infiltration rate of 0.6 to 1.9 h^{-1} which is much higher than what was found by Offerman (2008) and Price and Sherman (2006) in Californian homes. A lower infiltration rate would conserve energy but increase the impact of occupant behaviour on the energy consumption.

Recently, Sardianou (2008) investigated the determinants for space heating consumption by means of a questionnaire survey. She found that the age of the respondent, family size, annual income, and size and ownership status of the dwelling impacted the consumption of oil used for space heating. This indicates that the socioeconomic status has an impact on the behaviour patterns of occupants. These studies showed that occupant behaviour does indeed have a very large effect on the energy performance of buildings. This underlines the need for guidelines or models of behaviour patterns for implementation in simulation programs.

3.3 Real and simulated occupant behaviour

The development of codes for whole building simulation has previously focused on the physical aspects of energy use such as heat loss through the façade, solar gain through windows etc. The current standard of most codes are very efficient at predicting the energy consumption of a building with specified occupant behaviour. However, specification of the behaviour of the occupants has received little attention. The following section describes some of the consequences of this negligence.

Bishop and Frey (1985) compared the energy consumption of two passive solar town houses in Pittsburgh and Pennsylvania with their design energy use. They found the measured energy consumption to be more than twice as high as the predicted consumption. This discrepancy was a result of differences in the real occupant behaviour from the behaviour used in the predictions.

Machintosh and Steemers (2005) conducted a post-occupancy evaluation case study in an urban housing scheme in London. The apartments were equipped with operable windows and a mechanical ventilation system with heat recovery. Based on the results from the evaluation and observations of window opening behaviour, they derived a linear relationship between the outdoor temperature and the proportion of open windows. This was used to calculate the CO_2 emissions from the energy consumption in the building, which was compared to the CO_2 emissions of the theoretical optimum energy consumption for which the systems were designed. The result was that the actual use of windows and mechanical ventilation system bore no resemblance to the theoretical model. In fact, the actual energy consumption resulted in a CO_2 emission of roughly 1.5 times that of the theoretical model. In this case the designers simply assumed that the occupants would use the windows in an optimal way. It is difficult to assess how widespread invalid assumptions of occupant behaviour are in the design of buildings, but apart from the Humphreys adaptive model in ESP-r [Rijal et al. (2007)], a model proposed by Herkel et al. (2005), and the SHOCC model proposed by Bourgeois (2005), there are no guidelines describing how to deal with the behaviour of the occupants when designing buildings. While these models do offer some help on the simulated window opening behaviour, they only take thermal effects into account, even though window opening behaviour has been shown to depend strongly also on other variables [Paper I, paper II, Johnson and Long (2005)]. Furthermore all these models were developed using data from offices and are as such only valid in offices. The aim of the present PhD project was to identify factors which influence occupant behaviour. A model that take most of these factors into account was developed to simulate the window opening and heating set-point behaviour of occupants in dwellings.

For each behavioural control action there might be several and different triggers (e.g. thermal, visual, acoustical or air quality related triggers). Clarke et al. (2006) described how the triggers might be considered as an element in a control loop for the sensation of comfort. In this loop, sensors, control laws and actuators are all different between individual occupants. For example, in a given environment one person might be comfortable while another is feeling uncomfortably hot. According to the adaptive principle, the uncomfortable person will react in ways which will cool him down. Given several control opportunities, the occupant might choose just one or several of them. For example, he might open a window, remove a piece of clothing, drink or eat something cold or he might do it all. Different occupants might select different controls when acting to regain comfort. Furthermore, it is unlikely that different occupants will react at the same level of discomfort. Due to these intrinsic uncertainties, realistic modelling of occupant behaviour should be based on a probabilistic rather than a deterministic approach.

STUDIES

This PhD project studied the topic of occupant behaviour. The project began by reviewing literature. A simulation study (described in paper IV) was conducted in the beginning of the project to assess the extent of the impact of occupant behaviour on the energy performance of buildings. The simulation study was followed by an extensive questionnaire survey, conducted to identify factors with an influence on control related behaviour of occupants. The results from the survey were reported in paper I and in two conference papers. The conference papers are not included in this thesis as large parts of the method sections and discussions would be repetitions. Instead the results reported in the conference papers are presented in section 5.

As a follow up on the questionnaire survey, monitoring of control actions taken by the occupants and environmental variables were carried out in 15 dwellings (paper II). This led to a definition of control related behaviour patterns that were implemented in a building simulation program. A small study was carried out to assess the effects on energy performance of using the derived patterns instead of a ‘normal’ consultant approach. The behaviour patterns are defined as probabilities of an event taking place. In the definition these probabilities are calculated based on the indoor and outdoor environment and can be implemented directly in most simulation programs. The implementation in IDA ICE and the small study is described in section 7.

The results of the first simulation study showed that the control related behaviour of occupants has a substantial impact on the energy performance of a building. This becomes increasingly important in buildings designed using the adaptive model of thermal comfort, where occupants are encouraged to interact with building controls. Simulation studies were conducted to compare consequences for occupant performance and energy consumption of applying temperature criteria set according to the adaptive model of thermal comfort and the more conventional PMV model (paper III).

4 SIMULATION OF THE EFFECTS OF OCCUPANT BEHAVIOUR ON ENERGY CONSUMPTION IN BUILDINGS (PAPER IV)

To estimate the effect of occupant behaviour on the energy consumed to heat, ventilate and illuminate a building, a simulation study was carried out. The simulations were carried out using the dynamic building simulation software IDA ICE version 3.0 build 15.

4.1 Methods

The model consisted of a single room (4 m x 7 m) with a single occupant and was located in Copenhagen, Denmark.

The simulated occupant could manipulate four different controls to adjust the environment (table fan, window opening, blinds, and heating) and two controls by which the occupant could adjust to the environment (clothing insulation and metabolic rate). All control actions were carried out with the aim of keeping the PMV value within predefined limits in accordance with CR1752 (1998). Both energy consuming and energy efficient behavioural patterns were simulated. In both behaviour patterns, three limits for the PMV index were set in accordance with the guidelines in CR1752 (1998) (+/-0.2, +/-0.5 and +/-0.7 for quality categories A, B, and C, respectively), resulting in a total of six simulations. A seventh reference simulation was made during which the occupant had no control over the environment. In this simulation the occupant only controlled the clothing insulation and the metabolic rate.

Table 1: Setup of the simulations.

Criteria	Energy expensive behaviour pattern	Energy efficient behaviour pattern
A (-0.2<PMV<0.2)	Simulation 1A	Simulation 2A
B (-0.5<PMV<0.5)	Simulation 1B	Simulation 2B
C (-0.7<PMV<0.7)	Simulation 1C	Simulation 2C

An example of the energy expensive and energy efficient behaviour patters is given in figure 2. In behaviour pattern 1 the fan was turned on if the PMV increased to 0.1. If the PMV continued to increase the window was opened at 0.2, the blinds were lowered at 0.3 and a piece of clothing was removed at 0.4. At a PMV value of 0.5, the metabolic rate reached the minimum value and the heating was turned off at a PMV value of 0.6. When the occupant started to feel cold, the heater was turned on, metabolic rate and clothing was increased, blinds opened, window closed and the fan was turned off, in that specific order.

In behaviour pattern 2 the order of events were inverted, so the occupant turned off the table fan as the first thing when he felt cold and turned off the heater as the first thing when feeling warm. For criteria A and B the increments in PMV value between events were decreased to fit the +/- 0.5 and +/- 0.2 criterion.

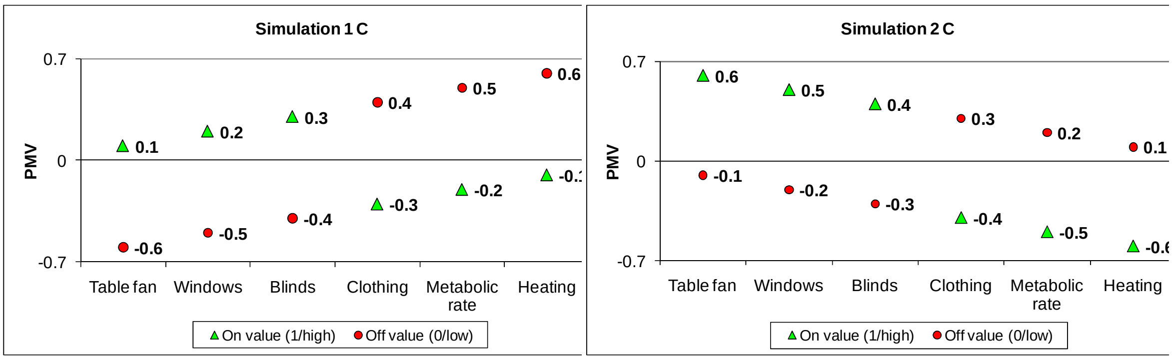

Figure 2: Control schemes for energy expensive and energy efficient behaviour patterns in criteria C.

4.2 Results

The main purpose of the simulation study was to assess the extent to which occupant behaviour affects building energy. The main results of the simulations were that occupant behaviour affected the energy consumption by up to 330 % (3984 kWh/1198 kWh). The behaviour patterns affected the energy consumption in the room by up to 324 %, while the control criteria affected the energy consumption by up to 117 %. Consequently the occupant's control pattern impacted the energy consumption more than the criteria by which the thermal environment was controlled.

The results of the study underlined the importance of taking occupant behaviour into account when designing buildings.

Table 2: Energy consumption in the seven simulations. The primary energy was calculated according to the Danish building code by multiplying the electrical consumption by a factor of 2.5.

energy consumption pr. Year [kWh/year]	1A	1B	1C	2A	2B	2C	No control
Heating	2532	2372	2346	923	768	720	1812
Fan	380.1	423.6	431.0	1.4	0.3	0.1	0.0
Circulation Pump	13	13	13	3	2	2	13
Lighting	174	172	171	187	189	189	131
Primary energy for heating, ventilation and lighting	3948	3891	3882	1400	1246	1198	2171

5 QUESTIONNAIRE SURVEY OF OCCUPANT BEHAVIOUR AND ENVIRONMENT (PAPER I)

The scope of the questionnaire survey was to identify factors with influence on the behaviour of occupants in Danish dwellings. The survey was web based and was conducted in September and October 2006 and again in March 2007. Invitations to participate in the survey were sent to homes that were randomly selected according to dwelling size, dwelling age, ownership conditions, geographical location and the type of heating in the dwelling. The addresses were obtained from a Danish database with information about all dwellings in Denmark. In addition to the address, information such as size, age, heating system and ownership conditions of each dwelling was obtained from the database.

Meteorological data was obtained from 25 measuring stations in Denmark [Danish Meteorological Institute].

Four controls were investigated: Window open/closed, heating on/off, light on/off and solar shading in use/not in use. The investigation consisted of the elaboration of statistical models describing the relationship between the four controls and selected explanatory variables.

5.1 Statistical methods

As a preliminary analysis and to compare with the results obtained by Nicol and Humphreys (2004), logistic regression was used to infer the probability of the states of four controls with the outdoor temperature as the only explanatory variable.

The main analyses of the data from the questionnaire survey consisted of the elaboration of models inferring the probability of the state of one control each.

In the main analyses the effects of explanatory variables (and relevant second-order interactions) on the ‘state’ of the dwelling were analysed separately by means of multiple logistic regression analysis using a generalized additive model with binomial link [Hastie and Tibshirani (1997)]. Continuous covariates were modelled using a smooth nonlinear function, since their effect on behaviour cannot be assumed linear a priori. Significance of variables was tested based on a likelihood ratio test using a 5% significance level. In identifying the final model for each outcome, only cases with all relevant questions completed were included in the analysis.

In all the analyses data from both the winter and summer surveys was used. The data was analysed assuming independence. Backward selection was used to reduce the full models by removing all non significant variables from the models. In the final reduced models with only significant relationships between explanatory and response variables all relationships turned out to be very close to linear. As a consequence, all four final models were inferred using multiple logistic regressions without the use of smooth nonlinear functions. A more detailed presentation of logistic regression is found in paper II.

5.1.1 Odds ratio

Logistic regression was used to infer the probability of the state of the dwelling. In paper I it was decided to report the effects of the explanatory variables as odds ratio (OR), i.e. the ratio between the odds at different levels of an explanatory variable. The odds are defined as the probability of success divided by the probability of failure (in the case of windows it is the probability of an open window divided by the probability of a closed window).

5.2 Results from the questionnaire survey

The main results of the questionnaire survey were that window opening behaviour in Danish dwellings was strongly linked to the outdoor temperature. Other factors such as solar radiation, floor area, ownership conditions of the dwelling, gender of the respondent and the perception of environmental variables (IAQ, noise and illumination) also affected the proportion of dwellings with open window.

The use of heating was strongly related to the outdoor temperature and the presence of a wood burning stove in the dwelling. Variables such as solar radiation, ownership conditions of the dwelling and the perception of indoor environmental variables (IAQ and Illumination) also affected the use of heating. The use of lighting was strongly correlated to the solar radiation, perceived illumination and outdoor temperature. The average age of the inhabitants, the respondents' thermal sensation and gender also had an influence on the use of lighting in Danish homes.

5.2.1 State of the Dwelling and Outdoor Temperature

Figure 3 is a depiction of the logistic regression models fitted to the data using only outdoor temperature as the explanatory variable. At any outdoor temperature, Figure 2 shows the probability of an open window, heating on, etc. The inferred probabilities of open window and of heating on were similar to the relationships found by Nicol and Humphreys (2004) in European office buildings, suggesting that the outdoor temperature has the same effect on the window opening and heating behaviour of occupants in European offices and Danish dwellings.

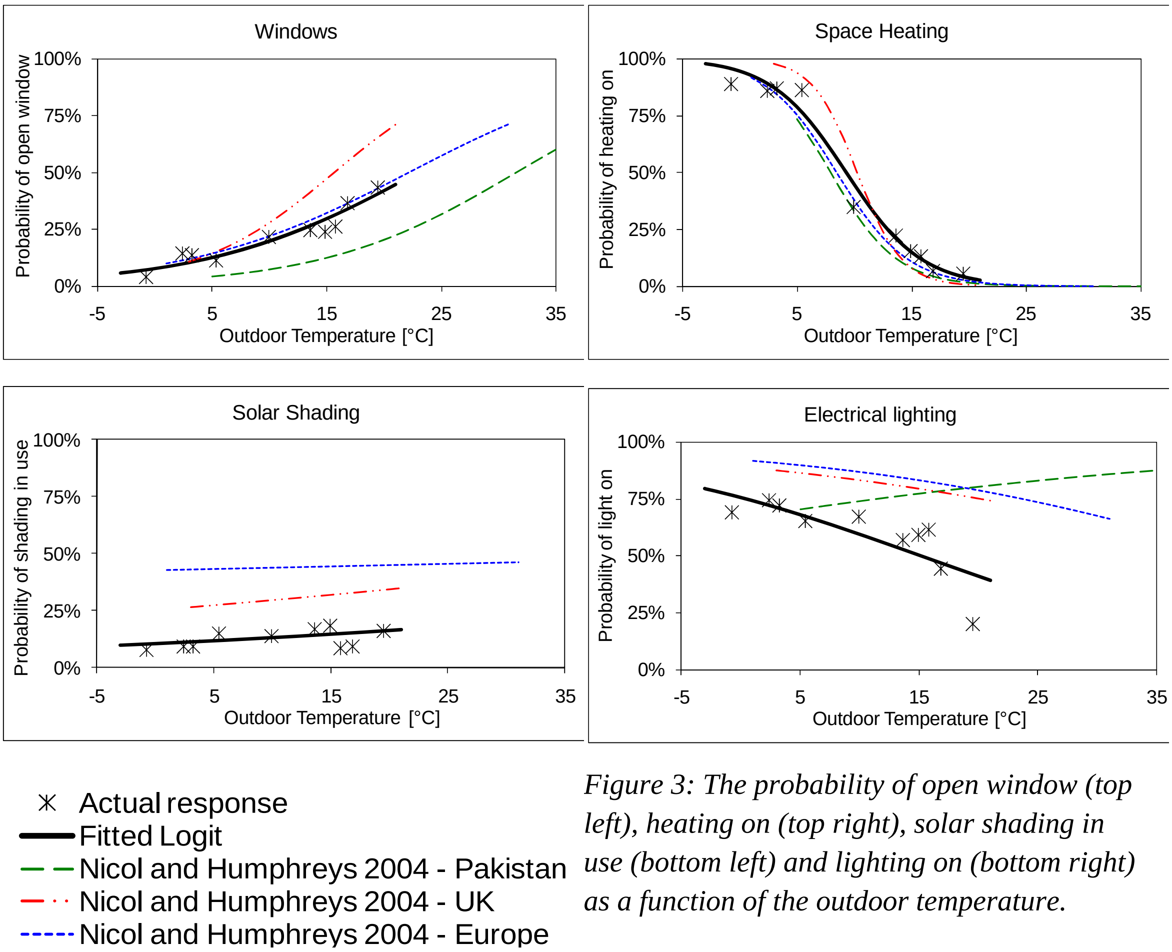

Figure 3: The probability of open window (top left), heating on (top right), solar shading in use (bottom left) and lighting on (bottom right) as a function of the outdoor temperature.

The inferred probability of using solar shading varied very little as a function of the outdoor temperature, suggesting that outdoor temperature was not a significant predictor. There was a slight increase in the probability as the outdoor temperature increased. This could be an effect of more sunshine in warm periods of the year. The probability of blinds/curtains in use as observed by Nicol and Humphreys (2004) was much higher than in the Danish Dwellings, suggesting that solar shading is more widely used in European offices than in Danish dwellings.

The probability of having the light on was lower than the findings of Nicol and Humphreys (2004) and decreased with increasing outdoor temperature. As with the solar shading, this could be an effect of more daylight in warm periods.

5.2.2 Reasons for opening and closing windows

The most significant reasons for opening the window or door to vent during both summer and winter were that the respondents wanted more air movement. In summer, many respondents agreed that they opened the window because it was hot inside.

Table 3: Distribution of responses to agreement in reasons for opening the window for the summer and winter survey. The table is a result of responses to the question: The window or door was opened to vent because…

		It was hot inside the dwelling	Condensation on windows	The air felt dry	The air smelled bad	I wanted more air movement	I needed to contact someone outside
I agree	Summer	58 %	18 %	9 %	38 %	81 %	10 %
	Winter	18 %	39 %	16 %	47 %	80 %	12 %
I do not agree	Summer	30 %	64 %	69 %	47 %	11 %	68 %
	Winter	67 %	48 %	67 %	41 %	14 %	69 %
I don't know/no answer	Summer	12 %	18 %	22 %	15 %	8 %	22 %
	Winter	15 %	13 %	18 %	11 %	6 %	19 %

The most significant reasons for closing the windows or doors during summer was that the respondent had to leave the dwelling, the temperature was right or that it was too cold in the dwelling. In the winter case the most significant reasons were that it was too cold in the dwelling, the respondent had to leave the dwelling, the bad smell was gone and that it was draughty.

Table 4: Distribution of responses to agreement in reasons for closing the window for the summer (top) and winter survey (bottom). The table is a result of responses to the question: The window or door was closed after venting because…

	The temperature was right	The bad smell was gone	Too much noise outside	too cold in the dwelling	Smoke or bad smell outside	There was a draught	papers were flying around	I had to leave the dwelling
I agree	64 %	41 %	14 %	50 %	10 %	49 %	9 %	77 %
	46 %	53 %	6 %	64 %	7 %	51 %	6 %	55 %
I do not agree	24 %	42 %	68 %	37 %	71 %	36 %	71 %	15 %
	41 %	35 %	78 %	27 %	77 %	37 %	77 %	33 %
I don't know/no answer	12 %	17 %	18 %	14%	19 %	15 %	20 %	8 %
	13 %	12 %	16 %	9 %	16 %	12 %	17 %	12 %

5.2.3 Agreement between residents on the heating set-point

In the summer survey 21% of the respondents not living alone answered that the residents in the dwelling could not agree on the set-point for the heating in the dwelling. In 70% of these cases the person who wanted the highest set-point was a female, whereas a male wanted the lowest set-point in 69 % of the cases. This indicates that when occupants do not agree on the heating set-point, it is the female who feels cool and the male feels warm. This confirms the findings of Karjalainen (2007), who observed that females used heating controls to achieve higher room temperatures than males did.

Fanger (1973) showed in laboratory studies using same clothing for men and women, that there was no difference in the preferred room temperature between males and females, when subjected to the same conditions. The reason for the different preference regarding room temperature set-point could be that females felt colder and males felt warmer due to differences in clothing or that men are more concerned about the heating costs.

5.2.4 Actions when feeling hot and cold

When asked to state one to three actions when feeling hot and when feeling cold, the most common reply in the summer survey was to adjust clothing, to adjust the heating set-point a little, and to open the window (only when feeling hot).

Table 5: Adaptive actions when feeling hot or cold. The table shows the proportion of responses. The respondents were asked to state one to three actions, so the proportions do not add up to 100 %. Proportions larger than 50 % are highlighted in bold.

	Too cold in winter	Too Hot in winter	Too cold in summer	Too Hot in summer
Large heating set-point adjustment	5%	15%	6%	22%
Small heating set-point adjustment	**66%**	**67%**	**78%**	**64%**
Build a fire in oven (only too cold)	29%		9%	
Clothing adjustment	**82%**	**81%**	**86%**	**79%**
Movement	16%	1%	17%	2%
Cold/hot shower	6%	1%	5%	2%
Blanket (only too cold)	12%		12%	
Drink or eat hot/cold	21%	12%	20%	12%
Other	3%	3%	3%	3%
Do nothing	1%	2%	3%	2%
Open window (only too hot)		**60%**		**68%**

The results suggest different clothing behaviour between offices and dwellings. In dwellings the main adaptive action was to adjust clothing. However Baker and Standeven (1996) found that office occupants rarely altered their clothing ensemble on an hourly basis.

In the summer survey 64% replied that they would turn down the heating when feeling too warm. The exact question in the survey was: ‘Imagine that you are to warm. What would you do to cool off?’ It is assumed that the respondents who stated that they would decrease the heating set-point imagined that they were feeling too warm as a result of a too high heating set-point.

5.2.5 Age and gender composition of respondents

In order to investigate how representative of the Danish population the respondents and the inhabitants of the dwellings were, the age and gender composition of the three groups were compared.

Table 6: The gender composition of the respondents, the inhabitants of the respondents' dwellings and of the total Danish population.

Gender	Respondents	inhabitants	Danish Population
Female	37%	51%	51%
Male	63%	49%	49%

The gender composition of the respondents differed from the Danish population. However, the gender composition of the inhabitants of the surveyed dwellings was similar to that of the Danish population.

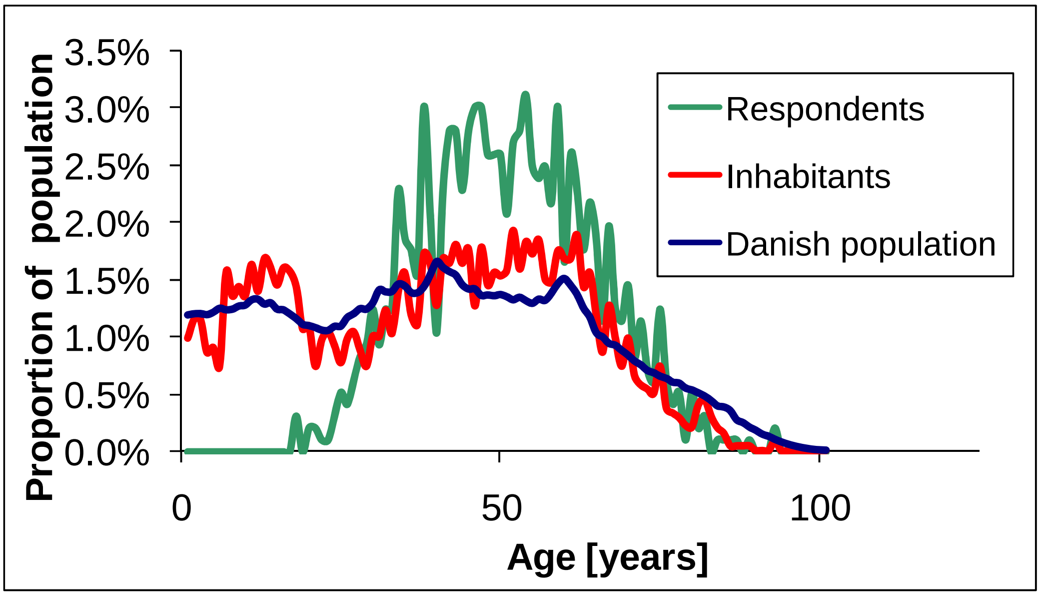

Figure 4: Age composition of the respondents, the inhabitants of the respondents' dwellings and of the total Danish population.

In the invitation to participate in the survey it was stated that only persons older than 18 years of age could participate in the survey. As a consequence, none of the respondents were younger than 18 and a larger proportion than in the Danish population were between 35 and 65. The age composition of the inhabitants in the surveyed dwellings reassembled the Danish population.

5.3 Discussion of the questionnaire survey

The main findings of the questionnaire survey (reported in paper I) were determinations of factors affecting the sate of the building. Furthermore the relations between the factors and the state of the building were derived. The probability of having a window open and the probability of having the heating on were affected similarly in Danish dwellings and in European offices. Furthermore, reasons for window opening behaviour and behaviour when feeling thermal discomfort was examined.

5.3.1 Thermal sensation and window opening

The thermal sensation vote of the respondents did not have a significant impact on the window opening behaviour. This is probably due to the fact that opening a window affects the indoor environment and thereby the thermal sensation. The window might have been opened due to thermal discomfort, but when the respondent filled in the questionnaire he or she might have been thermally comfortable again (while the window remained open). If the window remained open until the respondent felt cold, a thermal sensation vote from those with windows open would have been anywhere in the range from hot to cold.

5.3.2 Validity of the questionnaire survey

Do the results obtained in the survey reflect the real behaviour of the general population? In order to answer that question several aspects must be examined. The aim of the survey was to investigate the behaviour of the general population in Denmark. However, in order to do so by a questionnaire survey, several factors must be considered:

5.3.2.1 Representativeness

In order to study the behaviour of a population the respondents must be somewhat representative of that population. E.g. if there are no respondents in the age from 50 to 60 then the survey cannot be used to conclude anything about that age-group. Invitations to participate in the survey were sent by post to addresses that were selected so they were representative of the Danish housing stock on five parameters. In order to ensure that the respondent population was also representative on those parameters, it was tested if there were any differences between the respondents and those who did not respond to the invitation. Some differences between the two groups were found but they were regarded as being so small that they could be neglected.

The gender and age composition of the respondents and of the inhabitants was compared to that of the Danish population. In doing so it was found that the respondents differed from the Danish population but both the age and gender composition of the inhabitants in the surveyed dwellings resembled the Danish population. The main analyses were done using responses about the state of the window, heating, lighting and solar shading. Any of the inhabitants in the dwelling might have opened/closed the window, adjusted the heater etc. and as such it is the inhabitants and not the respondents that should be regarded as the main group of interest.

5.3.2.2 Validity of the responses

When constructing a questionnaire it is important that the respondents and the authors interpret the questions and responses similarly. In order to ensure this, a pilot study was conducted in which six subjects were asked to fill in the questionnaire in the presence of the authors. After the completion of the questionnaire all subjects were interviewed about their interpretation of the questions and responses. Minor adjustments were made to the questionnaire after the two first interviews.

Another question regarding the validity of the responses is if respondents can be trusted? Or put in another way; do respondents do what they say they do? That question has been extensively studied and it is beyond the scope of this thesis to go further into detail in this question. However, it should be mentioned that most research show that if certain aspects are considered in the formulation of questions and in the construction of the questionnaire, it is likely that the respondents will answer truthfully to the questions. For further information, the following books can be consulted: Olsen H (2006), Olsen H (2005), Hansen EJ and Andersen BJ (2000)

5.3.2.3 Reliability of the analyses

If the data collected in the survey are analysed incorrectly the results of the survey might be invalid. The reliability of the methods used in the questionnaire survey was discussed in paper I.

6 MEASUREMENTS OF WINDOW OPENING AND HEATING SET-POINT BEHAVIOUR IN DWELLINGS (PAPER II)

Measurements of window opening and heating set-point behaviour along with indoor and outdoor environmental variables were conducted in 15 dwellings in the vicinity of Copenhagen, Denmark, during the period from January to August 2008.

6.1 Measuring methods

Measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated while the other half were equipped with constantly running exhaust ventilation in the kitchen and bathroom. Three single family houses were naturally ventilated while the other two were equipped with exhaust ventilation.

When sending invitations to participate in the monitoring program, the aim was to find occupants who spent most of their time in their dwellings. Since the results of the questionnaire survey showed that age did not affect the behaviour of the occupants, an attempt was made to conduct the measurements in dwellings where at least one of the inhabitants was retired. As a consequence, the average age of the occupants was higher than in the general Danish population.

The measurements were carried out in one living room and one sleeping room in each dwelling.

The following variables were measured in 10 minute intervals in all 15 dwellings.

- Indoor environment factors
  - Temperature [°C]
  - Relative humidity [%]
  - CO2 concentration [ppm]
- Outdoor environmental factors
  - Air temperature [°C]
  - Relative humidity [%]
  - Wind speed [m/s]
  - Solar radiation [W/m²]
- Behaviour
  - Window state (open/closed)
  - Angle of windows [°]
  - Temperature set-point of thermostatic radiator valves (TRVs) [°C]

In the main analyses, the probability of opening or closing a window (change from one state to the other) was inferred rather than the probability of an open window (state). This was done by splitting the data in two databases based on the state of the window. The probability of an opening and closing event was inferred using multivariate logistic regression with interactions between selected variables.

Linear regression was used to deduce the angle of the window and the temperature set-point of the TRVs.

6.2 Results of the measurements

The analyses of the data showed that the behaviour of the occupants was governed by different, but distinct, habits in the 15 dwellings. This applied to both the window opening and the heating set-point behaviour. Table 7 shows the result of the analysis of the window opening and closing behaviour using logistic regression. For each variable the coefficients for the logistical regression is shown for different times of day and day of week. The magnitude of the variable is a measure of the maximum impact of the variable on the probability of opening or closing a window.

Table 7: Results of the analyses of the probabilities of opening and closing windows. The magnitude is a measure of the impact of the variable on the probability. It was calculated as the numerically largest coefficient of the variable multiplied by the scale of the variable.

		Open		Close	
Variable		Coefficient	magnitude	Coefficient	Magnitude
Intercept during weekend	Night	-8.55	-	-4.08	-
	Morning	-5.08		5.57	
	Day	-6.67		7.35	
	Evening	-6.61		6.36	
Intercept during workday	Night	-8.32	-	-3.88	-
	Morning	-4.85		5.77	
	Day	-6.44		7.55	
	Evening	-6.38		6.56	
Indoor temperature	Night	0.002585	1.10	-0.8107	-12.2
	Morning	0.009908		-0.3025	
	Day	0.07336		-0.1871	
	Evening	0.011616		-0.2357	
Indoor Relative humidity	-	-	-	0.03942	1.6
CO2 concentration	Night	0.001018	2.38	-0.0037	-7.8
	Morning	0.000566		-0.00059	
	Day	0.000158		-0.00179	
	Evening	0.001134		-0.00039	
Outdoor temperature	Night	0.060408	2.30	-0.5343	-20.3
	Morning	0.043587		-0.267	
	Day	0.012418		-0.2153	
	Evening	0.026525		-0.2019	
Wind speed during weekend	Night	0.002489	0.03	0.36406	4.7
	Morning	0.002489		0.05866	
	Day	0.002489		0.01184	
	Evening	0.002489		0.02274	
Wind speed during workday	Night	-0.04236	-0.55	0.3241	4.2
	Morning	-0.04236		0.0187	
	Day	-0.04236		0.0518	
	Evening	-0.04236		0.0627	
Outdoor Relative humidity	-	-	-	-0.02261	-1.6
Solar radiation during Weekend	Night	0.001089	1.09	-0.00045	-1.7
	Morning	0.001089		-0.00167	
	Day	0.001089		-0.00086	
	Evening	0.001089		-0.00098	
Solar radiation during workday	Night	0.000482	0.48	-0.00045	-1.7
	Morning	0.000482		-0.00167	
	Day	0.000482		-0.00086	
	Evening	0.000482		-0.00098	

The outdoor temperature, indoor temperature and the indoor CO2 concentration were the most important variables in determining the window opening/closing probability.

The indoor temperature, CO_2 concentration, Outdoor temperature and solar radiation were positively correlated with the probability of opening the window, whereas an increase in wind speed resulted in a lower probability of opening the window during workdays. In the weekends the wind speed had very little impact on the window opening probability.

The probability of closing a window was positively correlated with the wind speed and negatively correlated with the indoor temperature, CO_2 concentration, outdoor temperature and solar radiation.

The most influential variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

Table 8: Results of the model of the trv set-point. The R^2 for the model was 0.31. The magnitude is a measure of the impact of the variable on the probability. It was calculated as the numerically largest coefficient of the variable multiplied by the scale of the variable.

variables	time of day	unit	coefficients	magnitude
Intercept during workdays	morning	-	23.76	-
	day		24.82	
	evening		23.99	
	night		23.29	
Intercept during weekends	morning	-	23.80	-
	day		24.86	
	evening		24.02	
	night		23.32	
CO_2 concentration	-	ppm	0.00048	0.8
Outdoor temperature	morning	°C	-0.30	-12.5
	day		-0.32	
	evening		-0.33	
	night		-0.31	
wind speed during workdays	morning	m/s	-0.08	-2.6
	day		-0.20	
	evening		-0.06	
	night		0.02	
wind speed during weekends	morning	m/s	-0.01	-1.7
	day		-0.13	
	evening		0.01	
	night		0.09	
outdoor relative humidity	-	%	-0.063	-4.4
Solar radiation	-	W/m²	-0.0006	-0.6

The outdoor temperature, solar radiation and outdoor relative humidity were negatively correlated with the trv set-point indicating that the heating set-point was increased when these variables decreased.

When the window was open the indoor relative humidity, wind speed, solar radiation indoor and outdoor temperature affected the angle of opening.

The results presented in tables 7 and 8 constitute a definition of occupant behaviour patterns that can be used in building simulation programs. Since the definition was based on monitoring of real behaviour patterns, the definition will significantly increase the validity of the simulation outcome when implemented into simulation programs.

7 SIMULATION OF THE EFFECTS OF BEHAVIOUR PATTERNS ON ENERGY CONSUMPTION AND INDOOR ENVIRONMENT

To investigate the effects of the behaviour patterns derived from the measurements and described in paper II, simulations were conducted in the dynamic building simulation software IDA ICE [IDA ICE Version 3 build 16]. The model consisted of a single room in a single family house located in Denmark. The room had two outer walls facing south and east. The room had five windows (height: 1.5 m, width: 1.2 m) and two waterborne heaters under the windows.

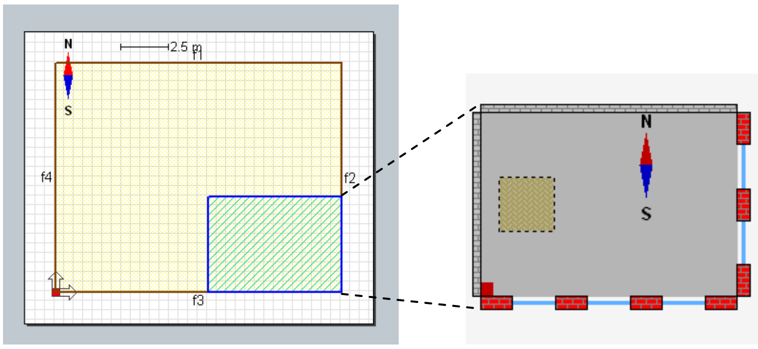

Figure 5: The simulated building seen from above (left). The room that was simulates is marked in blue. The layout of the windows in the room is shown to the right.

The simulated building had one crack in each exterior wall. All cracks connected the interior of the building to the exterior environment. The local wind pressure coefficient of the faces of the building was determined according to the ASHRAE Handbook of Fundamentals (1997). The opening areas of the cracks were determined by running simulations with closed windows. The opening area of the cracks were adjusted with the aim of an average infiltration rate of 0.19 h^{-1}. This aim was based on a study by Kvistgaard et al. (1985) who measured the average infiltration rate (with closed doors and windows) in 14 Danish dwellings ventilated by natural ventilation and obtained an average infiltration rate of 0.19 h^{-1}.

7.1 Simulated behaviour

Two behaviour patterns were simulated: A case that simulated the behaviour patterns described in paper II and a reference simulation with behaviour patterns defined like they might have been by a consultant engineer.

In each time-step the probability of opening and closing a window was calculated based on the logistic regression coefficients described in paper II. The results of the calculations were the probability of opening/closing a window within the next 10 minutes. Like most simulation programs, IDA ICE is deterministic rather than probabilistic in nature. As a result the probability of an event had to be translated to a deterministic signal. A way of doing this is to compare the probability to a random number to determine if the event takes place or not. As the given probability is the probability of an event in the next 10 minutes, the comparison was made with a random number that changed every 10th minute. Two time series of evenly distributed random numbers between 0 and 1 with an interval of 10 minutes were loaded into IDA ICE. These numbers were then compared with the probability of opening and closing a window (one series for opening and another for closing). The window was opened or closed if the random number (that changed every 10th minute) was smaller than the calculated probability. In the event that both the random open number and the random closing number were smaller than the calculated probabilities, the window position remained unchanged. Out of the five windows in the room one window in each wall was operable and opened and closed simultaneously.

When the windows were opened, the angle of the windows was calculated using the linear regression model described in paper II. This angle was then used to calculate the size of the opening of each operable window.

The heating set-point was determined by the regression coefficients described in paper II. Waterborne heaters were controlled by a p-controller with a dead band of 1 °C.

The occupancy was determined by a first order Markov-chain technique described by Richardson et al. (2008). An Excel sheet provided by Richardson et al. (2008) was modified to generate yearly (in stead of daily) time series of occupancy with a 10 minute resolution. This was used as input to determine the occupancy in the simulated room. The Excel sheet provided data on the number of occupants that were not asleep. The maximum number of occupants in the room was three. When there were no occupants present (or all occupants were at sleep), the windows were closed and the heating set-point remained unchanged.

A reference simulation was made where the heating set-point was 21 °C with a dead band of 2 °C all year round. The windows opened if the temperature exceeded 26 °C and closed again when the indoor temperature decreased below 22 °C. This simulation was conducted to investigate the effects of the behaviour model by comparing with a simulated that could have been conducted by a consultant.

7.2 Results of the behaviour simulations

During almost all of the time when the room was occupied, the indoor temperature was higher in the case than in the reference simulation. This was a result of a higher heating set-point during winter in the case simulation. In the reference simulation, the window opening behaviour was only influenced by the indoor temperature as opposed to the case simulation where many variables affected the window opening behaviour[3]. As a result, the indoor temperature was higher and the CO_2 concentration was lower in the case simulation compared to the reference simulation.

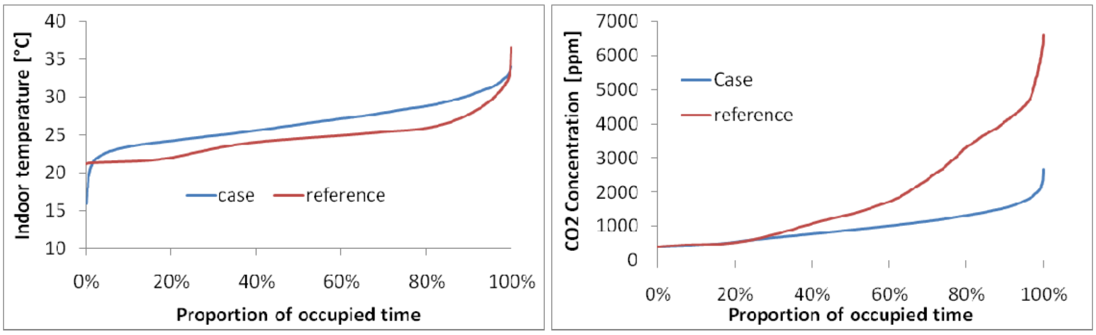

Figure 6: Duration curves for the indoor temperature (left) and the CO_2 concentration (right). The figure shows the duration (in percentage of the time when the room was occupied) the temperature and CO_2 concentration was below a certain level.

Most of the periods with high CO_2 concentrations occurred when the outdoor temperature was low. Since the window opening behaviour was only governed by the indoor temperature in the reference simulation, the windows were not opened even though the CO_2 concentration reached very high values. These values were not achieved in the case simulation since the CO_2 concentration affected the window opening behaviour in such a way as to increase the probability of opening a window with increasing CO_2 concentration.

The higher indoor temperature and the more frequent window opening resulted in a consumption of heat that was 317 % higher in the case than in the reference simulation. This is remarkably close to the difference of 330 % found in paper IV and again underlines the importance of considering the behaviour of the occupants in the design process of buildings.

[3] Indoor and outdoor temperature, wind speed, CO_2 concentration, indoor and outdoor relative humidity and solar radiation.

Table 9: Results from the simulations with behaviour patterns modelled as described in paper II (case) and as a conventional behaviour modelling as reference.

Simulation	Air change rate [h^{-1}]	Average indoor temperature [°C]	Average CO_2 concentration [ppm]	Heat consumption [kWh]	Electricity consumption for light [kWh]	Highest window opening frequency [opening events/day]
Case	0.90	26.7	882	872.8	868.5	11
Reference	0.61	24.7	1850	274.7	868.6	44

7.3 Discussion of simulation of behaviour patterns

The difference in heating consumption between the simulation with the occupant behaviour model and the reference model was 317 %. If the building had been designed using a behaviour pattern as in the reference, there would have been a very big risk that the actual energy consumption would have been larger than the calculated. The difference in the consumption between the two simulations was primarily due to a low heating set-point in the reference simulation. However, longer periods with open windows also contributed to the increased energy requirement in the case simulation.

Even though the windows were open for a longer time in the case simulation, the reference simulation had the highest daily opening frequency. An opening frequency of 44 opening events/day signifies that the window was opened on 44 occasions during a day. As a result the window was also closed 44 times on that day. Consequently, the window was adjusted 88 times/day or almost every 15th minute throughout the 24 hours. Such excessive window adjustment is regarded as unrealistic.

In the case simulation a random number was continuously compared to the calculated probability of opening or closing a window. This might have resulted in an opening of the windows even though the environmental variables were within comfort limits. This could have been avoided by only calculating the probability of opening a window if the environmental variables were outside comfort limits. I chose not to implement this approach for several reasons:

First of all the data from the measurements described in paper II, suggest that windows were sometimes opened based on the time of day rather than environmental variables. If I had chosen only to base window opening on comfort, the time dependent window openings would not have been modelled correctly.

Secondly, comfort limits are not easily defined. In thermal comfort, there are several methods of choosing limits for comfortable temperatures and the choice of model would influence the results. Furthermore, the model contains some measures of comfort implicitly. E.g. the probability of opening a window increases with increasing temperature (indoor and outdoor) and with increasing CO_2 concentration. Likewise the probability of closing a window increased with decreasing CO_2 concentration and indoor and outdoor temperature.

I chose to only have two operable windows in the model. The behaviour model described in paper II was developed based on measurements on two windows in each dwelling. The position of the other windows was not monitored. The windows that were monitored were the ones the occupants stated they opened most frequently. However, it is not known if the monitored windows were the only ones that were operated.

8 PERFORMANCE AND ENERGY SIMULATIONS WITH THE APPLICATION OF THE ADAPTIVE MODEL OF THERMAL COMFORT (PAPER III)

Occupant behaviour is especially important in buildings that are designed by the application of the adaptive model of thermal comfort. In buildings without mechanical cooling this model can be used to predict when occupants are thermally comfortable. However, little is known about the effects of using the model on productivity of occupants in offices. To investigate this, simulations were carried out in the simulation program IDA ICE [IDA ICE version 3.0 build 16]. The effects were investigated in four climates (Singapore, Sydney, San Francisco and Copenhagen) by simulation of a room with and without mechanical cooling in each climate. In the simulations of buildings with mechanical cooling, the conventional PMV model was applied to control the temperature, while the adaptive model was applied in buildings without mechanical cooling. The simulated temperature profiles were then used as input to a MATLAB procedure, which implemented a Bayesian network model of occupant performance.

In the naturally ventilated room, the temperature was controlled by adjusting window opening and radiator. In the mechanically ventilated room the temperature control was achieved with heating and cooling coils in the ventilation system and by a radiator. In the naturally ventilated room the temperature limits were set in accordance with the adaptive model in ASHRAE 55 (2004) as a function of the monthly average outdoor temperature. In the mechanically ventilated room the limits of the temperature comfort envelope was based on the PMV index using a metabolic rate of 1.2 Met. The clothing insulation was set as a function of the outdoor temperature at 6 o'clock AM, since De Carli et al. (2007) found that temperature to be the best predictor of clothing insulation.

8.1 Results of the performance and energy simulations

In all four climates the indoor temperature exceeded the upper limits for longer periods in the naturally ventilated buildings compared to the mechanically cooled buildings. This was especially evident in Singapore where the temperature exceeded the limit nearly 100% of the hours during occupancy in the building without mechanically cooling.

Table 10. Accumulated number of hours when the indoor temperature exceeded the upper comfort limit and percent of the occupied hours when the temperature fell in the ranges < 22°C, 22-26°C, and > 26°C.

		Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling	Accumulated hours (hrs) [a)]	2169	756	250	232
	% of hours with t < 22 °C [b)]	0	12.6	30.2	41.6
	% of hours with t ∈ 22 – 26 °C [b)]	0	52.1	62.7	53.6
	% of hours with t > 26 °C [b)]	100	35.3	7.1	4.8
With mechanical cooling	Accumulated hours (hrs) [a)]	103	93	99	98
	% of hours with t < 22 °C [b)]	0	0	0	0.8
	% of hours with t ∈ 22 – 26 °C [b)]	87.6	95.2	97.1	96.1
	% of hours with t > 26 °C [b)]	12.4	4.8	2.9	3.1

a) Accumulated number of hours during occupancy with temperatures above the upper comfort limit.

b) Percent of the occupied hours when the temperature fell in a given range

Table 11 summarizes the energy consumption in the eight simulations. In all simulations with out mechanical cooling the energy consumption was considerably lower than in the cases with mechanical cooling.

Table 11: Energy output from the indoor climate and energy simulations.

Location	Singapore		Sydney		San Francisco		Copenhagen	
Ventilation	Mech. Cooling	Non mech. cooling	Mech. Cooling	Non mech. cooling	Mech. Cooling	Non mech. Cooling	Mech. Cooling	Non mech. cooling
Heating [kWh]	0	0	984	6	2,115	17	5,521	86
Cooling [kWh]	31,226	0	6,033	0	772	0	301	0
Electrical [kWh]	9,752	8,279	9,755	8,236	10,957	8,259	10,395	8,291

The results of the occupant performance calculations are presented in table 12. In general, the annual performance index varied only little across location and building configuration, despite the considerable differences in the simulated indoor temperatures.

Table 12. Performance indices determined from one-year simulations of indoor temperature.

	Performance index (%)			
	Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling	98.1	98.8	99.0	99.0
With mechanical cooling	98.9	99.0	99.1	99.1

The results indicate that determination of acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of the occupants.

9 DISCUSSION

9.1 Driving forces

The adaptive principle relies on the notion that discomfort is the driver for adaptive actions and as such for occupant behaviour. In the following, the drivers for window opening behaviour and heating set-point behaviour are discussed.

9.1.1 Window opening behaviour

The Humphreys adaptive model in ESP-r [Rijal et al. (2007)] takes thermal comfort into account. As discussed in paper II and in section 3.1.1.3 other factors such as air quality are significant drivers for window opening behaviour. Results from the measurements described in paper II suggest that not only environmental factors play a role. Some occupants opened their window at the same time every day, regardless of environmental factors. The methodology of using discomfort as a driver for window opening might be right in some cases; however occupants participating in the measurements accepted indoor temperatures as low as 10 °C when airing out, indicating that discomfort in one variable might cause a window opening event even though this might lead to discomfort in other variables. It seems that occupants are willing to make a trade-off between variables.

During visits to the dwellings where the measurements were conducted some occupants said that they opened windows to air the rooms two or three times a day, regardless of the environmental variables. They stated that they had been advised to air the dwellings three times a day to avoid problems with house dust mites and moisture related problems such as mould growth. The driver for this behaviour is neither thermal discomfort nor perceivable air quality problems, but a concern about health effects of a poor indoor climate. It is difficult to determine how important this driver is but the fact that the time of the day had an effect on the behaviour in dwellings suggest that it is a driver that needs to be taken into consideration in dwellings. If this is also the case in offices remains unknown. However the prevalence of SBS symptoms would promote health related drivers.

9.1.2 Window open probability and outdoor temperature – a comparison with other studies

The probability of an open window (state of the window) was analysed as a function of the outdoor temperature. Figure 7 shows the probability that the window was open as a function of the outdoor temperature for the measurements (paper II) and for the questionnaire survey (Paper I). For comparison, the results of Rijal et al. (2007), Haldi and Robinson (2008) and Nicol and Humphreys (2004) are displayed. It should be noted that these results were obtained in offices.

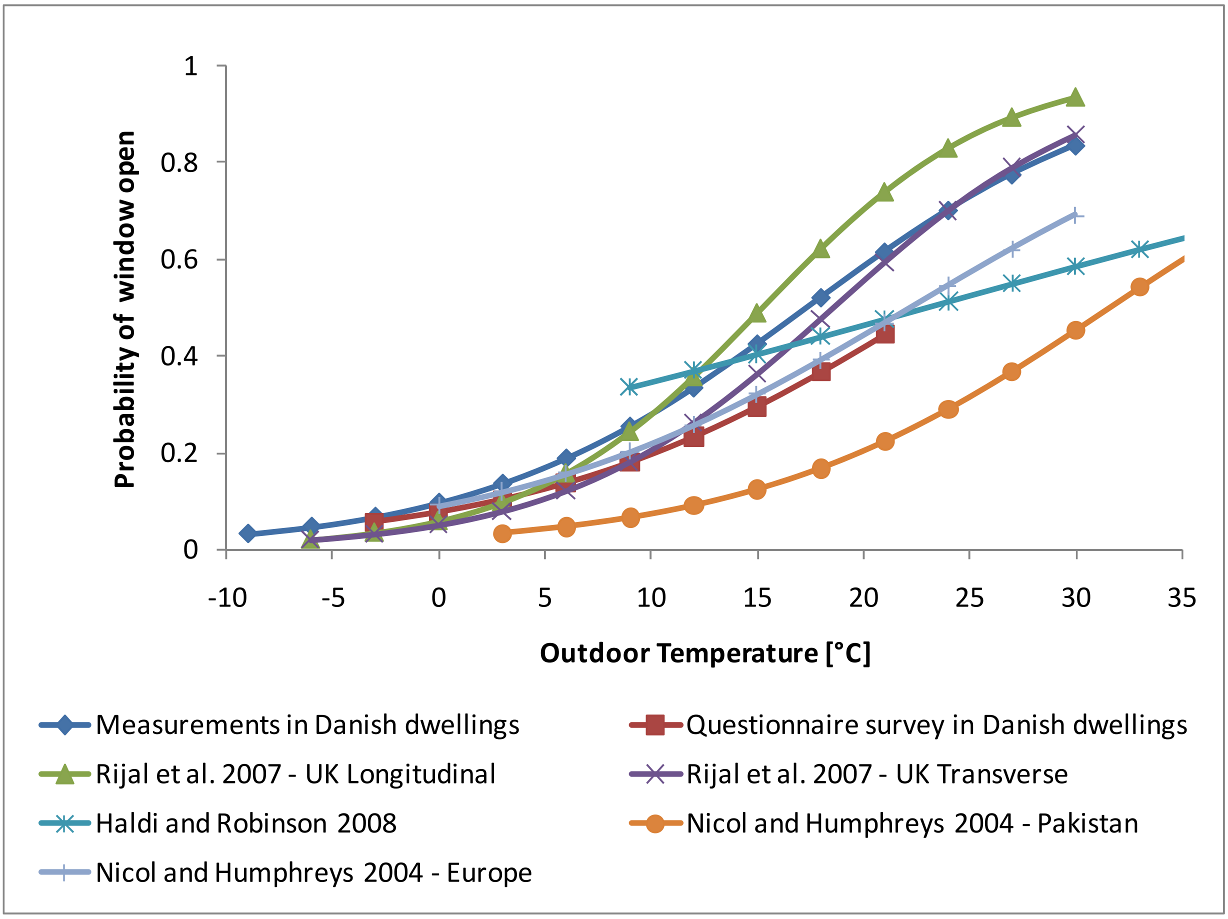

Figure 7: The probability of open window as a function of the outdoor temperature. The curves are results of logistic regression analyses

Apart from the results of the study by Nichol and Humphreys (2004) in Pakistan and Haldi and Robinson (2008) the relations depicted in figure 7 are similar. Studies have shown that window opening behaviour is not only governed by the outdoor temperature, but also by other variables that were not taken into account in figure 7. As a consequence, the curves in figure 7 can not be expected to be exactly the same. As such the comparison indicates that there is little difference in the effects of outdoor temperature on the window opening behaviour in offices and dwellings.

9.1.3 Heating set-point behaviour

The most influential variable on the heating set-point is most probably the indoor temperature. However the relationship between the indoor temperature and the adjustment of heating set-point is difficult to obtain since the indoor temperature is affected by the heating set-point. Because of this interaction, the indoor temperature was not included in the analysis of the data obtained from the measurements described in paper II. However, the research has uncovered several other important variables that affect the determination of the heating behaviour. Both the questionnaire survey and the measurements showed that the outdoor temperature and solar radiation has an impact on the heating behaviour. The wind speed did not have an effect on the heating behaviour in the questionnaire survey, but was found to be the third most important variable in the measurements. Parameters concerning the design of the dwelling such as ownership status and presence of a wood burning stove were also found to have a strong impact.

One of the few studies that have investigated heating set-point behaviour is the work done by Dubrul et al. (1988). They found a negative correlation between thermostat set-points and window opening behaviour: The higher the preferred thermostat setting was, the less windows were opened [Dubrul et al. (1988)].

Apart from a high proportion of open windows at low TRV set-point, this relation is not convincing in figure 8 which is based on the measurements described in paper II. The high proportion of open windows at low TRV set-points indicates that some occupants turned down the TRV set-point when opening the window and should not be taken as an indication of two different behaviour patterns.

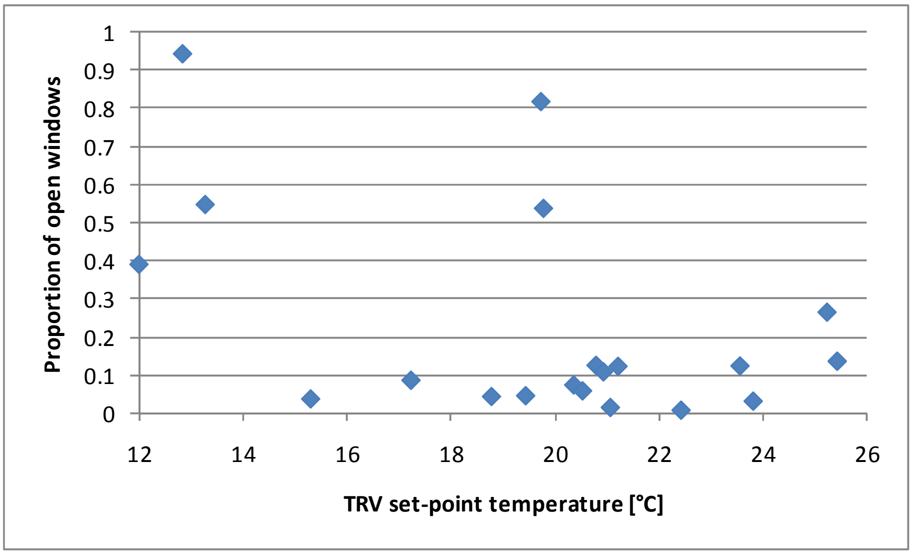

Figure 8: the proportion of open windows as a function of heating set-point. Each point represents 1/20 of the observations.

9.2 Implications of the conducted research

The results of the research conducted in the current project lead to a definition of occupant behaviour patterns that can be used in whole building simulation programs. It was realised that other factors than thermal effects impact the behaviour of occupants. These factors have to some extent been implemented in the model described in section 3.6.

The implications of the model are twofold: The model sets up a definition of behaviour patterns that can be implemented in simulation programs. If nothing else, a consequence of the model is that the behaviour patterns remain the same from one simulation to another, ensuring that the results are comparable. Secondly, as the model is based on the behaviour of real occupants and simulates changes in heating set-points and window opening behaviour, the results of building simulations will be closer to reality. This will dramatically increase the accuracy of simulation results, and enable designers to better assess the effects of the occupant's behaviour and thereby the effects of different design alternatives.

The model will not predict the behaviour of the occupants 100 % accurately. Occupant behaviour is highly individual and to some extent random. As a consequence, no model will be able to predict perfectly the behaviour of one particular occupant. However, the model confirmed the findings of others on the dependency of heating and window opening behaviour on thermal comfort parameters indicating that these relationships are valid in both offices and homes.

10 CONCLUSIONS

In the present thesis occupant behaviour with regard to control of the indoor environment and the effects on indoor environment and energy consumption was studied by means of a questionnaire survey, measurements and simulations. The main focus was window opening and heating set-point behaviour in dwellings. The following can be concluded from the investigations

- There were large differences in the behaviour of the occupants between dwellings.
- The time of day had a significant impact on the occupants' behaviour suggesting that environmental variables can not account for all the variance in the observed behaviour patterns.
- Window opening behaviour was mainly affected by temperature (indoor and outdoor) and indoor air quality[4]. Other weather variables (solar radiation, wind speed and relative humidity) as well as perception of the indoor environment, floor area and ownership conditions also affected the window opening behaviour.
- Heating behaviour patterns depended on weather variables such as outdoor temperature, solar radiation, wind speed and relative humidity. The presence of a wood burning stove and ownership conditions of the dwelling as well as indoor air quality[4] also affected the occupants' behaviour patterns regarding heating.
- Using the adaptive model of thermal comfort was found to mediate energy savings without affecting the mental performance of the occupants significantly.
- Using the conventional PMV model occupant behaviour was found to have much larger effects on the energy performance of the building than the choice of design criteria.
- Based on the measurements a definition of occupant behaviour patterns in building simulation programs was proposed. When implemented into simulation programs, this definition will significantly increase the validity of the simulation outcome.

[4] measured CO_2 concentration and perceived air quality in the questionnaire survey

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PAPER I

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Survey of occupant behaviour and control of indoor environment in Danish dwellings

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ABSTRACT

Repeated surveys of occupant control of the indoor environment were carried out in Danish dwellings from September to October 2006 and again from February to March 2007. The summer survey comprised 933 respondents and the winter survey 636 respondents. The surveys were carried out by sending out invitations to addresses obtained from a Danish register along with information on dwelling characteristics. Meteorological data was obtained from the Danish Meteorological Institute.

Four control mechanisms (window open/closed, heating on/off, lighting on/off and solar shading in/not in use) were analysed separately by means of multiple logistic regression in order to quantify factors influencing occupants' behaviour.

The window opening behaviour was strongly related to the outdoor temperature. The perception of the environment and factors concerning the dwelling also impacted the window opening behaviour.

The proportion of dwellings with the heating turned on was strongly related to the outdoor temperature and the presence of a wood burning stove. The solar radiation, dwelling ownership conditions and the perception of the indoor environment also affected the use of heating.

The results of the statistical analyses form a basis for a definition of standard behaviour patterns which can be used to make calculation of energy consumption of buildings more accurate.

1. Introduction

Buildings account for more than 40% of the energy consumption in the EU member states, and households are responsible for consuming more than 26% [1]. Consequently, reduction of the energy consumption in buildings is instrumental to the efforts of reducing the EU energy import dependency.

Naturally ventilated buildings may save energy compared to mechanically ventilated buildings. In order to ensure good performance of naturally as well as mechanically ventilated buildings, designers should take occupants' interactions with the building control systems into account. Some do this by simply controlling the most important parameters centrally in an effort to minimize the influence of occupant behaviour on the performance of the building. However, Leman and Bordass [2] found that occupants were more forgiving of buildings that provided good opportunities of occupant control. Also, Paciuk [3] found a very strong link between the degree of perceived control and thermal comfort. In fact, the perceived degree of control explained an equal amount of variation in thermal comfort votes as the thermal sensation and operative temperature. In agreement with their results Brager et al. [4] found a 1.5 °C difference in the neutral temperature between occupants with high and low degree of control over the windows.

Delegating indoor environment control to the occupants increases the difficulty of predicting the performance of the building as a whole. If the occupants can manipulate the temperature set-points, ventilation rates etc., the performance of the building as a whole may deteriorate and result in higher energy consumption. Because of this, it is important to take occupant's interactions with the control systems into account when designing buildings. One challenge is that occupant behaviour varies significantly between individuals. In effect, this variation in occupant behaviour may result in large variations in the energy consumption of buildings. For example, Bahaj and James [5] found that the electricity consumption in nine identical low-energy social housing units varied by as much as 600% in some periods of the year. Also Rathouse and Young [6] found that there was great variation in the use of heating controls between English homes. Seligman et al. [7] investigated energy consumption in 28

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identical town houses and found that the largest variation in energy consumption was two to one. Furthermore, the energy consumption of the houses depended significantly on the occupants.

Because of this link between occupant behaviour and energy consumption, there is a need to characterize occupant behaviour in order to forecast occupant interaction with building controls to account for occupant behaviour in the simulation of the performance of buildings. Most building simulation programs provide possibilities of regulation of the simulated environment by adjusting building control systems (opening windows, adjusting temperature set-points etc.). However, no guidelines or standards exist for how the simulated environment should be controlled in the programs. The definition of a set of standard behaviours that can be implemented in the building simulation programs would significantly improve the validity of the outcomes of the simulations. However, a definition of such standard behaviours must be based on the quantification of real occupants' behaviour.

As early as 1951 Dick and Thomas [8] looked at occupants' interaction with building controls. They found that external temperature alone accounted for over 70% of the variation in the number of open vents and windows. Additional 10% of the observed variance could be attributed to wind speed. In 1977 Brundrett [9] studied 123 dwellings and found that weather data explained between 64% and 68% of the variance in the number of rooms with open windows. Since then buildings have been tightened and energy prices have increased which means habits may have changed.

More recently Nicol and Humphreys [10] used data recorded in offices in five European countries and Pakistan to study effects of outdoor and indoor temperatures on occupant behaviour and four different ways of controlling indoor climate. Their study found that the outdoor and indoor temperatures affected the proportions of fans, heaters and windows being on or off/open or closed. The study was carried out in offices and focused on the relationship with temperatures. It did not include occupant behaviour in dwellings, where the triggers for occupant behavioural action may be different (e.g. private vs. corporate economy and expenses incurred in heating, etc.).

In order to identify the most important factors affecting the occupant's interaction with building control systems (window opening behaviour, use of heating, solar shading and electrical lighting) in dwellings, a questionnaire survey was conducted in Danish dwellings in the late summer of 2006 and again in the winter of 2007.

2. Methods

Invitations to participate in the summer survey were sent by regular mail to a sample of Danish dwellings that was selected so that it was representative of the Danish housing stock on the following parameters: dwelling size, dwelling age, ownership conditions, geographical location and the type of heating system in the dwelling. The invitation consisted of a letter inviting the occupant to log on to a website with a user-specific code and fill in the questionnaire. The addresses were obtained from a Danish database with information about all dwellings in Denmark. In addition to the address, information such as size, age, heating system and ownership conditions of each dwelling was obtained from the database.

The invitations to participate in the summer survey were sent to 5000 addresses in Denmark from the 25th to the 28th of September 2006. 52 invitations were not delivered due to wrong address, resulting in a sample size of 4948 dwellings. 17 people informed (by phone or post), that they did not have access to the Internet at home. These persons received a paper based questionnaire. All respondents who filled in the questionnaire before October 19th, 2006 participated in a lottery with 4 prizes of 1000 DKK (ca. 140 €).

The winter survey was conducted by sending invitations by email to respondents who entered their email address in the summer survey. The 17 people from the summer survey, who did not have access to the Internet, were sent a paper based questionnaire. The invitations for the winter survey were sent on February 14th, 2007. Two reminders were sent in the following weeks to those who had not responded to the invitations. Also in the winter survey, four prizes of 1000 DKK were offered to those who completed the survey in due time.

The study was approved by the local ethics review board.

The questionnaire contained questions on the following topics:

- Questions on the present state of the dwelling such as: 'Right now, is the solar shading in use?', 'Right now, is the window in the room you are sitting in open?', 'Right now, is the heating on?' and 'Right now, is the light in the room you are sitting in on?'.
- Age and sex of each occupant in the dwelling.
- Perceived indoor environment at the time of the response and during the previous 14 days.
- Questions regarding the behaviour during the previous 14 days.

Meteorological data was obtained from 25 measuring stations in Denmark for September and October 2006 and for February and March 2007 [11]. For each response, the geographical position (represented by the postal code) of the dwelling was used to find the closest meteorological measuring station. The time of the response was then used to obtain weather data from that particular measuring station resulting in hourly values for the outdoor air temperature, the wind speed 10 m above the ground and the solar radiation on a horizontal plane. Besides this, the number of hours with sunshine for each day was obtained for each of the responses.

The effects on the 'state' of the dwelling (window, heating, light and solar shading) of the following variables (and relevant two-way interactions) were analysed.

- Thermal sensation (TS) of the respondent (on the ASHRAE 7 point Visual Analogue (VA) scale) at the time of the response [12].
- Perceived Illumination by the respondent at the time of the response (on a VA scale).
- Perceived indoor air quality (IAQ) at the time of the response (measured on a VA scale).
- Perceived noise level at the time of the response (measured on a VA scale).
- Outdoor temperature at the hour of the response.
- Wind speed at the hour of the response.
- Outdoor solar radiation on a horizontal plane at the hour of the response.
- Hours of sunshine during the day of the response.
- Age of the respondent.
- Gender of the respondent.
- Number of residents in the dwelling.
- The average age of the residents.
- The gender composition of the residents.
- Floor area of the dwelling.
- Dwelling ownership information (owned by residents, rented or multi-ownership).
- Type of heating (Gas, oil, wood and electricity).
- Presence of a wood burning stove.

Table 1
Distribution of responses

Response Variable	Prevalence of 'open', 'on' and 'in use' responses	Prevalence of 'closed', 'off' and 'not in use' responses
Window	344 (22%)	1205 (78%)
Heating	688 (45%)	844 (55%)
Lighting	910 (59%)	640 (41%)
Solar shading	196 (13%)	1285 (87%)

- Material of outer walls.
- Type of dwelling (apartment, detached house, terraced house or other).
- Age of the dwelling.

2.1. Statistical methods

The four control mechanisms (window open/closed, heating on/off, lighting on/off and solar shading in use or not) were analysed separately by means of multiple logistic regression analysis using a generalized additive model with binomial link [13].

Continuous covariates were modelled using a smooth non-linear function, since their effect on behaviour cannot be assumed linear a priori. Significance of variables was tested based on a likelihood ratio test using a 5% significance level. In identifying the final model for each outcome, only cases with all relevant questions completed were included in the analysis.

In all the analyses data from both the winter and summer surveys was used. The data was analysed assuming independence. The statistical software R [14] was used for the statistical analyses.

Table 2
Odds ratio for the explanatory variables that had a statistically significant impact on the response variables

Variable (Reference)	Level/unit	Window opening		Heating		Lighting		Solar shading	
		OR	*p*	OR	*p*	OR	*p*	OR	*p*
Outdoor temperature	°C[a]	**1.11**	**<0.0001**	**0.72**	**<0.0001**	**0.97**	**0.0023**	NS	NS
Ownership[b] (Private)	Rented	**2.08**	**0.0039**	**0.32**	**0.0003**	NS	NS	**1.89**	**0.0106**
	Shared	1.29	0.3509	0.55	0.0885	NS	NS	1.08	0.8167
	Other	0.84	0.4929	**0.44**	**0.0049**	NS	NS	0.78	0.3743
Ownership[b] (Rented)	Shared	0.62	0.1387	1.73	0.2039	NS	NS	0.57	0.1369
	Other	**0.40**	**0.0032**	1.36	0.4280	NS	NS	**0.41**	**0.0116**
Ownership[b] (Shared)	Other	0.65	0.1860	0.79	0.5724	NS	NS	0.72	0.4189
Solar radiation[c] (None)	Low	**1.53**	**0.0155**	1.30	0.1679	**0.04**	**<0.0001**	0.80	0.2708
	High	1.21	0.2966	**1.79**	**0.0032**	**0.02**	**<0.0001**	1.37	0.0843
Solar radiation[c] (Low)	High	0.79	0.1577	1.38	0.1194	**0.52**	**<0.0001**	**1.73**	**0.0064**
Floor area[b]	log(m^2)[d]	**0.49**	**0.0019**	NS	NS	NS	NS	NS	NS
Perceived illumination	0 = too dark, 100 = too bright[e]	–[i]	**0.0021**	NS	NS	**0.97**	**0.0023**	NS	NS
IAQ	log(110-'vote')[f]	–[i]	**0.0052**	–[i]	0.3348	**1.54**	**0.0002**	**1.66**	**0.0002**
Thermal sensation[g] (Warm)	Neutral	NS	NS	NS	NS	–[i]	**0.0113**	NS	NS
	Cold	NS	NS	NS	NS	–[i]	0.1551	NS	NS
Thermal sensation[g] (Cold)	Neutral	NS	NS	NS	NS	–[i]	0.3089	NS	NS
Perceived noise[h] (quiet)	Neutral	–[i]	0.1333	–[i]	**0.0040**	NS	NS	NS	NS
	Noisy	–[i]	**0.0033**	–[i]	0.7571	NS	NS	NS	NS
Perceived noise[h] (noisy)	Neutral	–[i]	**0.0247**	–[i]	0.1114	NS	NS	NS	NS
Supplementary heating[b] (Wood burning stove)	Other	NS	NS	1.94	0.1427	NS	NS	NS	NS
	None	NS	NS	**1.71**	**0.0451**	NS	NS	NS	NS
	No info	NS	NS	**2.38**	**0.0003**	NS	NS	NS	NS
Supplementary heating[b] (Other)	None	NS	NS	0.87	0.7592	NS	NS	NS	NS
	No info	NS	NS	1.22	0.6299	NS	NS	NS	NS
Supplementary heating[b] (None)	No info	NS	NS	1.40	0.0751	NS	NS	NS	NS
Respondent's gender[b] (Female)	Male	–[i]	**0.0072**	NS	NS	–[i]	**0.0270**	NS	NS
Average age of inhabitants[b]	Years	NS	NS	NS	NS	**0.99**	**0.0166**	NS	NS
Age of respondent[b]	Years	NS	NS	NS	NS	NS	NS	**0.99**	**0.0337**

'NS' (Not significant) indicates that the explanatory variable did not have a significant impact on the response variable. A *p*-value larger than 0.05 indicates an OR not significantly different from 1. *p*-Values lower than 0.05 are highlighted in bold. The OR refers to the level of the variable compared to the reference.

[a] The Odds Ratio refers to every incremental change of 1 °C in the interval −3 °C to 20 °C.

[b] The *p* values for these variables might be too low. This is due to the assumption of independence between variables that might not hold true for these variables. This is discussed in more detail in Section 4.3.

[c] Due to the distribution of the solar radiation data the continuous variable was transformed into an interval so that 'None' = 0 W/m^2, 0 W/m^2 <'Low' ≤ 100 W/m^2 and 100 W/m^2 <'High'.

[d] The floor area was transformed to obtain a better distribution. The OR refers to a change of 1 log(m^2).

[e] The perceived illumination votes were cast on a VA scale with the labels 'too dark' and 'too bright' in the ends. The scale was divided in 100 parts.

[f] The vote was cast on a VA scale with the notation 'bad air quality' at one end and 'good air quality' at the other. The scale resolution was 100 so 0 = bad and 100 = good. The variable was transformed to obtain a better distribution.

[g] The thermal sensation votes were cast on a 7 point interval scale. Due to the distribution of the votes, the variable was transformed so that cold refers to votes between −3 and −0.1, neutral refers to votes between −0.1 and 0.1 and warm refers to votes between 0.1 and 3.

[h] The vote was cast on a VA scale with the notation 'Too noisy' at one end and 'Too quiet' at the other. The scale resolution was 100 so −50 = 'Too noisy' and 50 = 'Too quiet'. Due to the distribution of the votes, the variable was transformed so that quiet refers to votes between −50 and −5, Neutral refers to votes between −5 and 5 and noisy refers to votes between 5 and 50.

[i] The odds ratio is not displayed because the variable interacted with another explanatory variable.

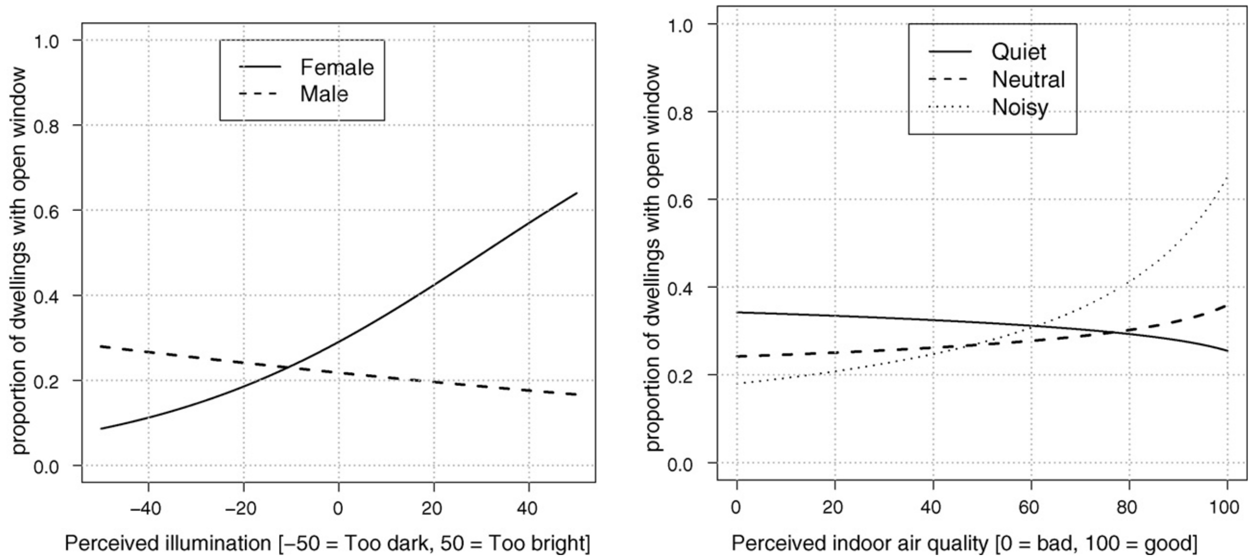

Fig. 1. Association between the proportion of dwellings with open windows and variables whose interaction affected this proportion significantly.

3. Results

974 respondents logged on to the website and 933 respondents completed the questionnaire in the summer survey, which means that 20% of the sample responded to the invitation and that 19% of the sample completed the questionnaire. Some of the 41 respondents, who logged on to the website without completing the questionnaire filled in parts of the questionnaire. Where possible their responses were used in the analysis.

In the winter survey an invitation mail was sent to 879 email addresses. 31 mails were returned by the mail server, because of invalid or unknown address. 649 respondents clicked on the link in the email and 636 respondents completed the winter questionnaire, meaning that 77% of the sample responded to the invitation and 75% of the winter sample completed the questionnaire.

Table 1 shows the distribution of the four response variables. In some cases the analysis data was incomplete because the respondent did not complete all the questions. This meant that between 1.2% and 5.6% the cases were excluded due to missing one or more covariates. As a consequence, each analysis was based on different number of responses. Our analysis leads us to believe that the nature of the missing data is not informative.

The results of the statistical analyses are presented in Table 2 in the form of odds ratios for explanatory variables that had a statistically significant impact on the response variable. In the cases where a significant interaction between variables occurred, the results are presented in Figs. 1–3.

The interaction between the respondent's gender and the perceived illumination had a statistically significant impact on the window opening behaviour. Also the perceived air quality and the perceived noise level interacted and affected significantly the window opening behaviour. This meant that females opened the window more often when perceiving the environment as bright as compared with dark, whereas the window opening behaviour of males was not affected by the perceived illumination. The interaction between perceived noise level and perceived air quality meant that the perception of a high noise level and good air quality led to an increase in the prevalence of open windows as compared with lower noise level and poor air quality.

Fig. 2 shows that the proportion of dwellings with the heating on was significantly affected by the interaction between the perceived air quality and the perceived noise level. This meant that a better air quality led to a decrease in the use of heating when the environment was perceived as too quiet or too noisy. In contrast, an increase in the use of heating was observed for an increase in air quality in environments perceived as having a neutral noise level.

Fig. 3 shows that the interaction between the gender of the respondent and the thermal sensation significantly impacted the proportion of dwellings with the lighting turned on. The interaction meant that the probability of the females having the lighting on was smaller when they felt warm or cold as compared with neutral. On the other hand, the probability of males having the lighting on was larger when they felt cold and warm as compared with neutral.

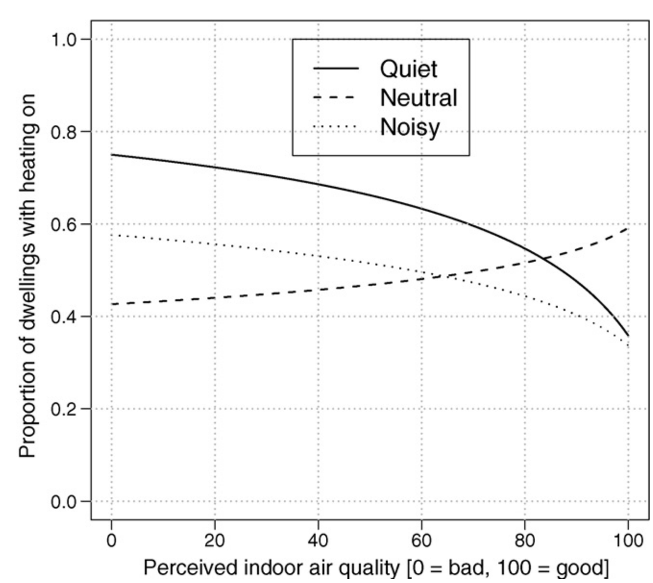

Fig. 2. Association between the proportion of dwellings with heating on, the perceived air quality and the perceived noise level.

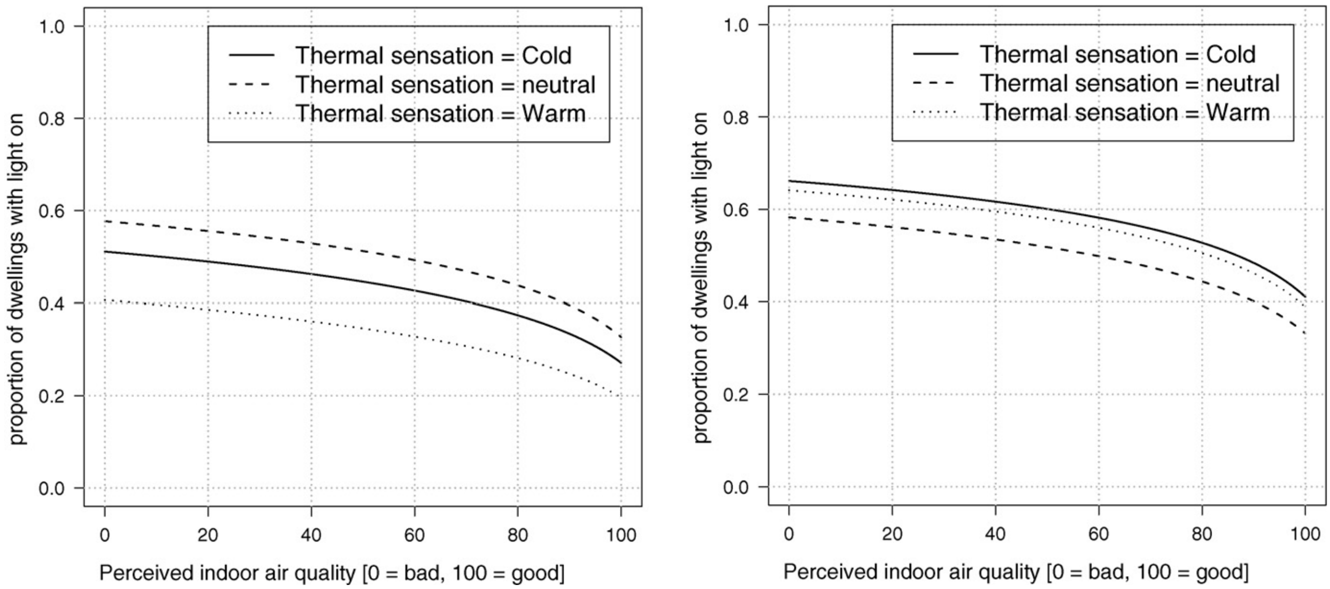

Fig. 3. Association between the proportion of dwellings with lighting on and thermal sensation for female (left) and male (right) respondents.

4. Discussion

4.1. Window opening behaviour

Not surprisingly the outdoor temperature had considerable impact on the window opening behaviour. This is consistent with a study by Rijal et al. [15], who found that the proportion of open windows was strongly related to the outdoor temperature. An earlier study found that the outdoor temperature was the single most important explanatory variable when investigating the number of open windows in 15 houses [8]. Brundrett [9] found the temperature (mean monthly temperature and average temperature swing) to be an important explanatory variable for the occupant's opening of windows. The study was based on average weekly weather data, which complicates a comparison of the current results with the results reported in reference [9]. Quantification of this dependency will be an important element in the definition of standard behaviour patterns.

It is worth noting that the wind speed did not affect the proportion of dwellings with open windows. This is inconsistent with earlier studies, which have found a significant decrease in the prevalence of open windows at high wind speeds [8,16]. In the current study, however, the wind speed was recorded at weather stations throughout the country at a height of 10 m above ground level. Even though the weather stations formed a relatively fine grid, local wind speeds might have differed from the ones recorded by the weather station.

The thermal sensation of the occupants was not a statistically significant predictor of the window opening behaviour. The reason for this might be the existence of a feedback mechanism in the sense that the opening of a window will affect the thermal sensation. If a window is opened because the occupants feel too warm, it will probably stay open until they start to feel cold. Because of this, occupants with open windows might have a thermal sensation anywhere between warm and cold.

4.2. Heating

As could be expected, the proportion of dwellings with the heating on was strongly linked to the outdoor temperature, but also the presence of a wood burning stove had a large impact on the control of the heating. The cost of heating did not influence the proportion of dwellings with heating on, suggesting that the price of heating did not hinder a comfortable temperature in the dwelling. The thermal sensation did not affect the heating behaviour significantly. This is probably due to the same feedback effect as for the window opening behaviour.

4.3. Validity of the results

In order to obtain a wide range of weather data, recordings from both the winter and summer surveys were used in the analyses. This means that some of the respondents appeared twice in the analysed dataset (once in the summer survey and once in the winter survey). Pooling of the data was based on the assumption that the summer and winter responses were independent due to the fact that even though some respondents might appear twice in the analyses their responses were half a year apart. If the assumption of independency does not hold true the result would be that the *p*-values obtained in the analyses may be too low.

In order to investigate the validity of the assumption of independence between summer and winter variables, statistical analyses were repeated using data from the summer survey only. When comparing the outcome of these analyses with the outcome of the analyses using pooled data from winter and summer, the same explanatory variables affected the response variables significantly. This supports the assumption of independence.

The two surveys were conducted during three-week period in late summer and late winter. Within each of these periods, the outdoor conditions changed somewhat, but as a consequence of the study being conducted in Denmark the outdoor conditions changed significantly from one season to another.

The analyses have shown that all response variables were affected by the outdoor conditions (temperature and solar radiation). Since outdoor conditions and season are strongly interrelated it is not possible based on the surveys to separate the effect of outdoor conditions and season. Thus, the results could be interpreted as behavioural differences between summer and winter period.

In the summer survey a response rate of 20% was obtained. Register data such as dwelling area, dwelling age, heating appliances, type of ownership, roof and wall material etc. was used to investigate if the group of those who did not respond differed from the respondents. For categorical data Pearson's X^2 test was used and a *t*-test was used for continuous variables. For some variables statistical significant differences between the two groups were observed. These differences were, however, so small that they were considered negligible. Due to the large number of respondents, the variation in age, building type, geographical location etc. it is assumed that the respondents were representative of the population of Danish households.

4.4. Defining standard behaviour patterns

The results of the questionnaire survey provided new insights on factors influencing occupant behaviour in Danish dwellings. These results form a framework for a definition of standard behaviour patterns that can be implemented in building simulation programs to improve their validity. At the present state, the results indicate which variables affect occupant behaviour given as odds ratios. These can be transformed into probabilities of different behaviours taking place. Most simulation programs, however, are deterministic rather than probabilistic. One possibility of a probabilistic to deterministic transformation is to choose a cut-off point in the probabilistic model, e.g., the window opens when the probability of the window being open exceeds 60% and closes when the probability decreases below 40%. A definition of standard behaviour patterns using this approach and the results of the questionnaire survey is in progress and will be reported in a future paper.

5. Conclusions

This questionnaire survey has shown that window opening behaviour in Danish dwellings was strongly linked to the outdoor temperature. Other factors such as solar radiation, floor area, ownership conditions of the dwelling, gender of the respondent and the perception of environmental variables (IAQ, noise and illumination) also affected the proportion of dwellings with open window.

The use of heating was strongly related to the outdoor temperature and the presence of a wood burning stove in the dwelling. Variables such as solar radiation, ownership conditions of the dwelling and the perception of indoor environmental variables (IAQ and Illumination) also affected the use of heating.

The use of lighting was strongly correlated to the solar radiation, perceived illumination and outdoor temperature. The average age of the inhabitants, the respondents' thermal sensation and gender also had an influence on the use of lighting in Danish homes.

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PAPER II

Long term monitoring of occupant behaviour and indoor environment in Danish dwellings

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ABSTRACT

Measurements of occupant's window opening and heating set-point behaviour were conducted in 15 dwellings in Denmark in the period from January to August 2008. Indoor and outdoor environmental conditions were monitored in an effort to relate the behaviour of the occupants to the environmental conditions. Logistical regression was used to infer the probability of opening and closing a window, while linear regression was used to determine the relationship between the environmental conditions and the heating set-point on thermostatic radiator valves.

The behaviour of the occupants was governed by different but distinct habits in the 15 dwellings. This applied to both the window opening and the heating set-point behaviour.

The outdoor temperature, indoor temperature and the indoor CO2 concentration was the most important variables in determining the window opening/closing probability.

The most influential variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

A method of defining occupant behaviour patterns in simulation programs based on the measurements is proposed.

KEYWORDS

Occupant behaviour, building controls, adaptation, window opening, heating set-point, Building simulation

INTRODUCTION

Occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer from fewer building related symptoms than occupants who are exposed to environments of which they have no control [1, 2, 3]. However, occupant behaviour varies significantly between individuals which results in large variation of the energy consumption of buildings [4,5,6]. Because of this, it is important to take occupant interaction with the control systems into account when designing buildings.

Most building simulation programs provide possibilities of regulating the simulated environment by adjusting the building control systems (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to very large of-set between simulation results and actual energy use [7]. Indeed Andersen et al. showed that differences in occupant behaviour might lead to differences in energy consumption of over 300 % [8]. Thus there is a need to set up standards or guidelines to enable comparison of simulation results between simulation cases. One method that can provide this is to define standard behaviour patterns that can be implemented in building simulation programs. This would significantly improve the validity of the outcome of the simulations. A definition of such standard behaviours should be based on the quantification of real occupant behaviour.

Two important parameters influencing energy consumption in dwellings are indoor temperature and air change rate. Wallace et al. measured air change rates in a house during one year and found that the opening and closing of windows had the largest effect on the air change rate [9]. Also Howard-Reed et al. found that opening of windows produced the greatest increase in air change rates compared with temperature differences and wind effects [10]. In Danish dwellings mechanical cooling is almost never used, which means that the indoor temperature depends on the heating set-point in winter and on the air change rate in the summer. As a consequence, window opening behaviour and heating set-point behaviour of occupants play an important role in determining the energy consumption and indoor environment of a household.

Recently, the effect of indoor and outdoor temperature on the window opening behaviour in offices has been investigated by means of logistic regression [11, 12, 13, 14]. The general trend has been to infer the probability of the window state as a function of indoor and outdoor temperature, while some have investigated the probability of opening a window (change from one state to another) as a function of indoor temperature [14]. Haldi and Robinson argued that the indoor temperature would be better a predictor than the outdoor temperature because indoor temperature is a driver for opening and closing windows to a much larger extent than outdoor temperature [12]. However, the indoor temperature is affected by the position of the window, which makes the analysis of window state based on indoor temperature difficult to interpret. The problem is that the predictive variable is influenced by the state that it is trying to predict. In a cold climate the low indoor temperatures would occur when the windows are open and not when they are closed. In such a case the result of the analysis would be that the inferred probability of a window being open increases with decreasing indoor temperature, with the illogical implication that the probability of opening a window would increase with decreasing indoor temperatures.

Another problem with this approach is that the driving forces for opening and closing a window might be different. The window might be opened due to IAQ and closed because of low indoor temperature.

Most recent studies have been limited to the investigation of thermal stimuli [11, 12, 13, 14] although other studies have found that other drivers play an important role in determining the window opening behaviour [15, 16].

In this paper we have inferred the probability of opening and closing a window (change form one state to another) separately, rather than investigating the state of the window. In this way the most dominating drivers for each action was derived and the problem of feedback on indoor environment from window state, overcome.

METHOD

Andersen et al. [15] quantified behaviour of occupants in Danish dwellings by means of a questionnaire survey. A definition of standard behaviour patterns was attempted, but a link to the indoor environment was missing due to the effects of behaviour of the occupants on the indoor environment. As a follow up to the questionnaire survey and to fill in this gap, simultaneous measurement of occupant behaviour, indoor and outdoor environment was carried out in 15 dwellings during the period from January to August 2008.

Measurements

The following variables were measured continuously in all 15 dwellings.

- Indoor environment factors measured every 10 minutes
  - Air temperature
  - Relative humidity (RH)
  - Illumination
  - CO2 Concentration

- Outdoor environment

    - Air temperature
    - RH
    - Wind speed
    - Solar radiation

- Behaviour
    - Window position (open/closed)*
    - Heating setpoint on thermostatic radiator valves.

*In three of the cases the actual opening angle of the window was also measured

The indoor environment measurements were carried out with Hobo U12-012 data loggers [17]. The CO_2 concentration was measured using a Vaisala GMW22 sensor [18] connected to the Hobo logger as depicted in figure 1. Both the CO_2 sensors and the Hobo data loggers were newly calibrated from the factory. The CO_2 sensors were tested against a newly calibrated Innova mulitgas analyser both before and after the measuring period. The temperature sensors in the hobo data loggers were also tested before the measurements. The Outdoor environmental variables were obtained from the Danish meteorological institute [19].

The window position (open/closed) was measured using a Hobo U9 sensor [17]. Three of the windows were hitched in the top and tilted outwards when opening. In these cases the tilt was measured using an accelerometer (HOBO UA-004-64 Pendant G) [17] attached to the window frame. In this way the opening angle of the window was measured.

The heating set-point was measured using custom made thermostatic radiator valves (trv). The trv's were equipped with a variable electric resistance attached so that the electrical resistance varied with the set-point of the trv. The electrical resistance was measured using Hobo U12-012 [17] data loggers. All trv's were calibrated before the measurements. Due to practicalities it was not possible to install the custom made trvs in two of the single family houses (one mechanically and one naturally ventilated) during the heating season. As a consequence the heating set-point was only monitored in 13 dwellings. Pictures of the measuring instruments are displayed in figure 1.

Generally, all measurements were carried out in one living room and one bedroom in each dwelling. However, in some of the dwellings the residents stated that they never turned on the heating in the bedroom. In these cases both thermostatic radiator valves were installed on radiators in the living room. The window sensors were installed on windows that inhabitants used most often when ventilating the dwelling.

The dwellings

Andersen et al. [15] found that ownership status of the dwelling (rented, owned etc.) influenced the behaviour of occupants in residences. Measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated (apart form an exhaust hood in the kitchen) while the other half was equipped with constantly running exhaust ventilation from the kitchen and bathroom. Three of the single family houses were naturally ventilated while the other two were equipped with exhaust ventilation.

With the exception of one (located 60 km from Copenhagen) all dwellings were located less than 25 km from Copenhagen.

Features of the dwellings are described in Table 1.

All apartments were located in two complexes, one with natural ventilation and one with mechanical exhaust ventilation.

All dwellings used waterborne radiators/convectors and natural gas boilers as a primary means of heating and two of the dwellings (number 10 and 16) had a wood burning stove.

PROCESSING AND PREPARATION OF DATA

The indoor environment sensors were placed on internal walls at a height of roughly 1.8 m above the floor. We attempted to place the sensors so that they would not be hit by direct sunlight, but due to acceptance of the occupants in the dwellings and other practicalities this was not always possible. In the cases when direct sunlight fell on the sensors the temperature measurements were corrected for the heating of the sensor. This was done in periods when the measured illumination level was larger than 1000 lux. In these cases the temperature was corrected by linear interpolation between measurements one hour prior to and one hour after direct sunlight fell on the sensor.

The CO2 concentration was used as an indicator of the occupancy of the rooms where the measurements took place. If the CO2 concentration was below 420 ppm and the window was closed the room was classified as being unoccupied. Furthermore if the CO2 concentration decreased and continued to decrease until reaching values below 420 ppm and the window was closed in the entire period, the room was classified as unoccupied during the entire period.

If the bedroom and the living room were both unoccupied, the dwelling was classified as unoccupied. Periods when the dwelling was unoccupied were not taken into consideration in the analysis.

Meteorological data was obtained from the weather station closes to each dwelling. The following variables were obtained in 10 minute intervals: Outdoor temperature, outdoor relative humidity, wind speed at 10 m above ground level, solar radiation on a horizontal surface, the number of minutes with sunshine. The meteorological data was merged with the indoor environment observations and the behaviour observations to form one database.

When analysing the window opening data the database was divided depending on the state of the window (open/closed) to infer the probability of opening and closing the window (change from one state to another) separately.

STATISTICAL METHODS

Multivariate logistic regression with interactions between selected variables was used to infer the probability of a window opening and closing event. The method relies on the probability function described in formula 1.

However, the probability might depend differently on x_1 at one level of x_2 as compared to another level of x_2 (e.g. an increase in temperature might increase the probability of opening a window at high CO_2 levels, whereas the same increase might result in a lower probability at low CO_2 levels). An example like the one described above would not be well described by a model based on equation 1. Equation 2 deals with interactions between variables by adding interaction terms to the model.

In the interpretation of the coefficients, the sign, the size and the scale of the corresponding variable have to be taken into account. E.g. an indoor temperature coefficient of 0.073 might seem to impact the probability more than a CO_2 concentration coefficient of 0.0011. However, when the scales of the two variables (indoor temperature: 14 °C to 28 °C, CO2 concentration: 400 ppm to 2500 ppm) are taken into account the picture changes: To get an indication of the magnitude of the impact from each variable, the coefficients for each variable was multiplied with the range of the variable. In the example described above the magnitude of the impact was $0.073 \cdot (28\text{-}14) = 1.03$ and $0.0011 \cdot (2500\text{-}400) = 2.4$ for the indoor temperature and the CO_2 concentration respectively.

We have used equation 2 to infer the probability of windows being opened or closed. The full model consisted of all major variables and interaction terms between selected variables. Wald tests were then used to test the significance of each term. The analyses were based on backward selection meaning that interaction terms and variables that did not have a significant impact on the probability were removed from the full model. The variable with the highest p-value was removed from the full model and the model was run again without that variable. The variable with the highest p-value was then removed from that model and so forth. In this way all interaction terms with p-values greater than 0.1 were removed from the model. The analysis resulted in models that are too complex for the current standard of simulation programs. To lower the level of complexity the data was reanalysed with evaluation of only interaction terms between continuous and nominal variables, e.g. indoor temperature and day of week.

Linear regression was used to infer the set-point of the thermostatic radiator valves (trv). Like for the window opening and closing actions backward selection based on analysis of variance was used to remove non-significant terms from the full model. This approach also resulted in a model that was too complex to incorporate in simulation programs. As for the window case the complexity was lowered by a reanalysis of the data, evaluating only interaction terms between continuous and nominal variables.

The opening angle of the three top hung windows was analysed by linear regression. The full model with interaction terms and a model with no interaction terms yielded similar R^2 values and the model with no interaction terms was thus chosen for further analysis. The analyses were carried out on data from periods when the windows were open.

RESULTS

Variables in the first model for window opening and closing are listed in Table 2. The p-values are a result of Wald tests of significance of each term in the models with all non-significant variables and terms removed.

It is seen that some variables did not affect the probability of opening the window. These variables were not removed from the model because their interaction terms were significant. The models showed that the number of the dwelling affected the impact of nine and eight of the explanatory variables as concerns the probability of opening and closing a window, respectively. This indicates different habits in the 15 dwellings, which were not described by the measured variables. E.g. the time of the day interacted with the dwelling number, indicating that the windows were opened and closed at different (but distinct) times in each dwelling.

The objective of the measurements was to define standardised occupant behaviour patterns, suited for simulation purposes. The many interaction terms in table 2 show that occupant's window opening behaviour is governed by complicated relations between many variables. An attempt to define behaviour patterns must therefore rely on more than just the outdoor and indoor temperatures in order to realistically mimic the real behaviour. However, a model with many interaction terms between continuous variables may be too impractical for the current standard of simulation programs. Because of this, we have prepared a simpler model with a limited number of interaction terms between continuous and nominal variables. In this model we have not included the number of the dwelling and the type of room, since we are not interested in the behaviour in each single dwelling and room, but in the overall behaviour in all of the surveyed dwellings.

As expected, the indoor temperature, CO_2 concentration, Outdoor temperature and solar radiation were positively correlated with the probability of opening the window, whereas an increase in wind speed resulted in low probability of opening the window during workdays. In the weekends the wind speed had very little impact on the window opening probability.

The probability of closing a window was positively correlated with the wind speed and negatively correlated with the indoor temperature, CO_2 concentration, outdoor temperature and solar radiation.

The three most important variables in determining the probability of opening a window were the CO_2 concentration, outdoor temperature and the indoor temperature. This was also the case for closing of a window, although the order was different.

Degree of opening

The opening degree of the window was measured on windows that were opened by tilting outward. Three of the monitored dwellings had one such window. The results were analysed by linear regression

The model in table 4 estimates the angle between an open top-hung window and vertical, meaning that the window was closed at an angle of 0 ° and fully open at an angle of 90 °. For some combinations of the variables, the model results in negative angles, which means that the window opened inward? All of the windows in the dwellings opened outward. The coefficients in the equation were derived empirically. Empirically derived equations may sometimes lead to solutions that are unphysical. As a consequence negative angles should be regarded as 0°.

The indoor temperature affected the angle of opening negatively, meaning that the angle decreased and the window opening decreased with increasing indoor temperature. The same applies for the indoor RH and the wind speed. As could be expected the outdoor temperature and the solar radiation had the opposite effect resulting in larger opening at high values of solar radiation and outdoor temperature compared to low values. The angle of opening was largest in the morning during weekends and smallest during afternoons on workdays.

Heating

The heating set-point was monitored by measuring the set-point of two trvs in 13 dwelling. The set-points' dependency on indoor and outdoor environment was deduced using multivariate linear regression with interactions between selected variables.

As table 5 shows, the trv set-point was affected by almost all the measured variables and by many of the interaction terms. Both the number of the dwelling, the room and almost all interaction terms including these in the full model impacted the trv set-point significantly. In fact, the R^2 decreased from 0.86 to 0.45 when the variable 'number of the dwelling' and all its' interaction terms were removed from the model. This means that the occupants' trv set-point behaviour differed from one dwelling to another and even between bedroom and living room within a dwelling.

Because the results of table 5 are too complex for most simulation programs the data was reanalysed with a reduced number of interaction terms in the full model.

Essentially, the indoor temperature was affected by the temperature set-point and then the variables were not independent, which is a requirement of this analysis. As a consequence it is not a suitable predictor of the trv set-point and was removed from the model.

The outdoor temperature, solar radiation and outdoor relative humidity were negatively correlated with the trv set-point indicating that the heating set-point was increased when these variables decreased. The magnitude indicates that the most important variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

BEHAVIOUR PATTERNS IN SIMULATION PROGRAMS

The results from the analysis with a limited number of interaction terms provide a possibility of defining behaviour patens for simulation purposes. The results presented in table 6 can be used to determine the heating set-point of thermostats. Table 3 provides a method for calculating the probability that the window will be opened or closed during the next 10 minutes. A comparison with a random number can determine if the window is opened/closed or not. When the window is opened, table 4 provides information on the degree of opening.

DISCUSSION

Rijal et al. [11] describes three different assumptions that designers have made in the past when modelling window opening behaviour:

"(1) A schedule of windows open is assumed, based on occupancy, with or without evidence from the field.
(2) Window opening is assumed to be controlled by temperatures, humidity, wind, rain, based on assumptions about behaviour. Again evidence from the field is often absent.
(3) Windows are controlled to produce a given air flow rate or air exchange rate, may be more related to indoor air quality or minimum ventilation rather than thermal comfort. This approach assumes the occupant will utilize the window openings to achieve the design ventilation rates." [11]

It is clear that these three strategies of modelling occupant behaviour will lead to differences in the simulated indoor environment and in the simulated energy consumption of the building. An implementation of the model described in section 4 into a simulation program would significantly improve the validity of the simulation results in two ways: First of all it would enable comparability of results from different models, since they would be based on the same behaviour patterns. Secondly, because the behaviour in the model is based on real behaviour it has a better chance of mimicking the behaviour of the occupants in the building and thus getting the indoor environment and energy consumption correct.

Place of Measurement

Our measurements were limited to two rooms in each dwelling. Brundrett found that windows were most commonly found in the bedroom, particularly the main bedroom, while the sitting room, kitchen and the dining room had the lowest frequency of open windows [21]. This was later backed by Dubrul [22] who found that bedrooms were the main ventilation zone, whereas the greatest percentage of windows which were never opened was in the living rooms. Furthermore the percentage of open windows in kitchens and bathrooms was similar to that of living rooms. Based on these findings we chose to conduct the measurements in the main bedroom and in the main living room in each dwelling.

Statistical approach

We have used logistic regression to infer the probability of a window opening or closing event. In using this method we have assumed that the probability function looks like formula 2. Additionally we have assumed that all observations were independent of each other. This assumption is questionable as the observations were gathered in 15 dwellings. Essentially the assumption would hold true if all inhabitants of the dwellings reacted similarly to the conditions they were subjected to. In any other case the observations in each dwelling will be influenced by the habits of the inhabitants of the individual dwelling and as a result they would not be independent from each other. We have dealt with this problem by using the number of the individual dwelling as a factor in the model. In this way the variance between dwellings due to the habits of the inhabitants is accounted for in the model and the observations can be regarded as being independent.

In the more simple model described in table 3 the number of the dwelling was removed which means that the assumption of independence between variables no longer holds true. The consequence of this is that variables that in reality do not impact the probability significantly will show up in the model as being significant. However, the simple model described in table 3 was derived from the model more complex model which included the dwelling number and only had significant variables.

Seasonal variations

The measurements were made during the winter, spring and summer. As a consequence the results in this paper are only valid for these seasons. There is however no evidence that the behaviour of occupants depends differently on the measured variables in the autumn than in other parts of the year. This means that the results can be assumed to representative of the entire year.

Variables for determination of window opening behaviour

As described in section 3, the outdoor temperature was the most important variable in determining the probability of opening and closing a window. In both cases the magnitude of the impact on the probability was roughly twice as high as for the indoor temperature. Robinson points out that using only the outdoor temperature as a predictor of the window position will lead to the illogical result that the occupants of adjacently located buildings would interact with controls with similar probability, even though the indoor stimulus within them could be dramatically different [20]. Haldi and Robinson suggest using only the indoor temperature as the indoor and outdoor temperatures are expected to be correlated. This will lead to a reduction in the quality of the model since '…it is not clear whether there is a direct influence of outdoor temperature on the window opening probability or whether this is indirect due to the intrinsic correlation between indoor and outdoor temperature.' This may be true for some buildings but in our case the correlation coefficient between indoor and outdoor temperature was 0.32. As a consequence any influence of outdoor temperature was not likely to be "indirect" and we included both the indoor and outdoor temperature in the models.

Johnson and Long [11] conducted a visual survey of residential window and door positions in North Carolina. They found that the window and door opening behaviour was affected by a number of variables including weather, dwelling characteristics and anthropological variables. An AIVC report [22] concluded that there were considerable differences in the ventilations behaviour's weather dependency, which indicates that other variables play a significant role in determining the ventilation behaviour. These results are in accordance with our work and underline the importance of taking more than the temperature into account when investigating the behaviour of occupants.

Variations in individual behaviour patterns

The fact that the dwelling number had a significant effect on both the window opening and trv set-point behaviour means that occupant behaviour differed between dwellings. This could be an effect of different sensitivities in the dose response relationship for each individual. It could also be an indication of the driving forces being different in each dwelling. E.g. one occupant might open the windows 10 minutes to ventilate the bedroom each day at 7 o'clock whereas another occupant might open the windows when he/she feels too hot or wants to improve the IAQ. These differences in behaviour patterns between dwellings could explain some of the difference in energy consumption observed by Hackett and Lutzenhiser and Seligman et al. [23, 6].

The difference in trv set-point behaviour from dwelling to dwelling could be a result of differences in the occupants' sensitivities to the variables governing their behaviour. It could however also be a result of misunderstandings in function of the thermostats. The findings of Sami Karjalainen [24] support this. He analysed the understanding of room thermostats in Finnish offices by means of a qualitative interview survey and found a variety of usability problems. Also Rathouse and Young [25] found usability problems and misunderstandings of thermostats which could lead to great variation in the use of thermostats. Wheil and Gladhart [26] found that the thermostat control patterns varied greatly amongst households but were stable within each household. This is consistent with our findings and would indeed lead to stable energy consumption within each dwelling and to variations between dwellings as observed by Hackett and Lutzenhiser and Seligman [23,6].

CONCLUSIONS

Measurements of window opening behaviour, heating set-point behaviour, indoor and outdoor conditions were carried out in 15 dwellings in the vicinity of Copenhagen, Denmark.

The results indicated that the behaviour was governed by different but distinct habits in the 15 dwellings. This applies to both the window opening and the TRV set-point behaviour.

The probability of opening and closing of windows were inferred using multivariate logistical regression. The outdoor temperature, the indoor temperature and the indoor CO_2 concentration were the three most important variables in determining the probability of opening and closing a window.

Correlations between environmental variables and set-point on the thermostatic radiator valves were found using linear regression. The most influential variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

Based on the measurements a definition of occupant behaviour patterns in building simulation programs was proposed. When implemented into simulation programs, this definition will significantly increase the validity of the simulation outcome.

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Figure 1

Figure captions

Figure 1: Pictures of the instruments used to measure the indoor environmental variables and window opening behaviour: top left: CO_2 monitor connected to a data-logger with built in temperature, relative humidity and illumination sensors. Top right: Window state sensor (open/closed). Bottom left: window state sensor (open/closed) and window position sensor. Bottom right: Custom made TRV, connected to a data-logger.

Table 1

Dwelling number	Type	Mechanical ventilated	Floor area [m²]	Year of construction (and renovation)	Number of residents	Average age of residents
1	House	Yes	126	1994	2	65
3	House	No	145	1928	2	57
4	House	No	130	1956 (1976)	2	70
5	Apartment	Yes	83	1981 (2001)	1	76
6	Apartment	No	86	1945	2	78
7	Apartment	Yes	83	1981 (2001)	2	63
8	Apartment	No	109	1945	2	55
9	Apartment	No	87	1945	3	35
10	House	Yes	190	1901 (1957)	2	59
11	Apartment	No	77	1945	1	71
12	Apartment	No	109	1945	2	64
13	Apartment	Yes	80	1981 (2001)	1	60
14	Apartment	Yes	85	1981 (2001)	3	28
15	Apartment	Yes	84	1981 (2001)	2	60
16	House	No	139	1967	4	26

Table 2

		Window opening	Window closing
Parametric Terms:	df	p-value	p-value
Indoor temperature [°C]	1	<0.0001	0.7033[1]
Indoor RH [%]	1	0.3632[1]	0.2311[1]
CO_2 [ppm]	1	0.0637[1]	0.0001
Time of day [night, morning, daytime, afternoon, evening]	4	0.0002	0.0239
Weekday [workday, weekend]	1	0.2480[1]	0.2570[1]
Outdoor temperature [°C]	1	0.0196	0.0002
Wind speed [m/s]	1	0.8287[1]	0.0001
Outdoor RH [%]	1	0.0025	0.2478[1]
Solar radiation [W/m²]	1	<0.0001	0.0012
Hours of sunshine [h]	1	0.0080	Ns
Room [living room, bedroom]	1	0.0180	0.0001
Dwelling number	13	<0.0001	<0.0001
Indoor tem · CO_2 concentration	1	Ns	<0.0001
Indoor temp · time of day	4	0.0010	0.0049
Indoor temp · Outdoor temp	1	<0.0001	0.0002
Indoor temp · dwelling nr	13	<0.0001	<0.0001
Indoor RH · Room	1	<0.0001	Ns
Indoor RH · dwelling nr	13	<0.0001	<0.0001
CO_2 concentration · time of day	4	0.0003	0.0002
CO_2 concentration · Outdoor temp	1	Ns	0.0033
CO_2 concentration · Weekday	1	0.0258	Ns
CO_2 concentration ·Solar radiation	1	<0.0001	Ns
CO_2 concentration · Room	1	Ns	<0.0001
CO_2 concentration · dwelling nr	13	<0.0001	<0.0001
Time of day · Weekday	4	0.0002	0.0102
Time of day · Outdoor temp	4	0.0011	<0.0001
Time of day · Wind speed	4	0.0034	0.0032
Time of day · Solar radiation	4	<0.0001	0.0004
Time of day · Room	4	<0.0001	<0.0001
Time of day · Dwelling nr	52	<0.0001	<0.0001
Weekday · Dwelling nr	13	0.0007	Ns
Outdoor temp · Wind speed	1	0.0006	Ns
Outdoor temp · Room	1	<0.0001	<0.0001
Outdoor temp · Dwelling nr	13	<0.0001	<0.0001
Outdoor RH · Room	1	0.0216	0.0046
Outdoor RH · Dwelling nr	13	Ns	<0.0001
Solar radiation · Room	1	0.0063	0.0011
Solar radiation · Dwelling nr	13	<0.0001	<0.0001
Sunshine hours · Dwelling nr	13	0.0026	Ns
Room · Dwelling nr	13	<0.0001	<0.0001

1) The variable did not have significant impact on the probability but the interaction with another variable did significantly affect the probability.

Table 3

		Open		Close	
Variable		Coefficient	magnitude	Coefficient	Magnitude
Intercept during weekend	Night	-8.55	-	-4.08	-
	Morning	-5.08		5.57	
	Day	-6.67		7.35	
	Evening	-6.61		6.36	
Intercept during workday	Night	-8.32	-	-3.88	-
	Morning	-4.85		5.77	
	Day	-6.44		7.55	
	Evening	-6.38		6.56	
Indoor temperature	Night	0.002585	1.10	-0.8107	-12.2
	Morning	0.009908		-0.3025	
	Day	0.07336		-0.1871	
	Evening	0.011616		-0.2357	
Indoor Relative humidity	-	-	-	0.03942	1.6
CO2 concentration	Night	0.001018	2.38	-0.0037	-7.8
	Morning	0.000566		-0.00059	
	Day	0.000158		-0.00179	
	Evening	0.001134		-0.00039	
Outdoor temperature	Night	0.060408	2.30	-0.5343	-20.3
	Morning	0.043587		-0.267	
	Day	0.012418		-0.2153	
	Evening	0.026525		-0.2019	
Wind speed during weekend	Night	0.002489	0.03	0.36406	4.7
	Morning	0.002489		0.05866	
	Day	0.002489		0.01184	
	Evening	0.002489		0.02274	
Wind speed during workday	Night	-0.04236	-0.55	0.3241	4.2
	Morning	-0.04236		0.0187	
	Day	-0.04236		0.0518	
	Evening	-0.04236		0.0627	
Outdoor Relative humidity	-	-	-	-0.02261	-1.6
Solar radiation during Weekend	Night	0.001089	1.09	-0.00045	-1.7
	Morning	0.001089		-0.00167	
	Day	0.001089		-0.00086	
	Evening	0.001089		-0.00098	
Solar radiation during workday	Night	0.000482	0.48	-0.00045	-1.7
	Morning	0.000482		-0.00167	
	Day	0.000482		-0.00086	
	Evening	0.000482		-0.00098	

Table 4

Coefficients		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		18.0	1.0	17.819	< 0.0001
Indoor temperature [°C]		-0.23	0.046	-4.925	< 0.0001
Indoor RH [%]		-0.230	0.0084	-27.222	< 0.0001
Outdoor temperature [°C]		0.08	0.020	3.998	< 0.0001
Wind speed [m/s]		-0.27	0.031	-8.509	< 0.0001
Solar radiation [W/m²]		0.0007	0.00036	1.81	< 0.0001
Daytime (Night)	Morning	0.66	0.36	1.857	0.0633
	Day	0.54	0.37	1.449	0.1475
	Evening	-0.54	0.34	-1.586	0.1127
Weekday (Workday)	Weekend	1.21	0.11	11.52	< 0.0001

Table 5

Variable	Df	Sum Sq	Mean Sq	F value	p-value
Indoor temperature [°C]	1	130 551	130 551	4.23E+04	<0.0001
Indoor RH [%]	1	3 479 123	3 479 123	1.13E+06	<0.0001
CO_2 concentration	1	484 731	484 731	1.57E+05	<0.0001
Time of day [night, morning, daytime, afternoon, evening]	4	37 136	9284	3.01E+03	<0.0001
Weekday [workday, weekend]	1	5431	5431	1.76E+03	<0.0001
Outdoor temperature [°C]	1	276 068	276 068	8.95E+04	<0.0001
Wind speed [m/s]	1	1049	1049	3.40E+02	<0.0001
Outdoor RH [%]	1	21 565	21 565	6.99E+03	<0.0001
Solar radiation [W/m²]	1	5619	5619	1.82E+03	<0.0001
Hours of sunshine [h]	1	163 264	163 264	5.29E+04	<0.0001
Room [living room, bedroom]	1	1 719 147	1 719 147	5.57E+05	<0.0001
Dwelling number	12	4 160 447	346 704	1.12E+05	<0.0001
Indoor temp : time of day	4	23 077	5769	1.87E+03	<0.0001
Indoor temp : Weekday	1	1497	1497	4.85E+02	<0.0001
Indoor temp : Wind speed	1	1037	1037	3.36E+02	<0.0001
Indoor temp : Solar radiation	1	5394	5394	1.75E+03	<0.0001
Indoor temp : Sunshine hours	1	1106	1106	3.59E+02	<0.0001
Indoor temp : Room	1	494	494	1.60E+02	<0.0001
Indoor temp : dwelling number	12	408 073	34 006	1.10E+04	<0.0001
Daytime : Weekday	4	64	16	5.15E+00	0.0004
Daytime : Outdoor temp	4	1540	385	1.25E+02	<0.0001
Daytime : Wind speed	4	4327	1082	3.51E+02	<0.0001
Daytime :Solar radiation	4	1447	362	1.17E+02	<0.0001
Daytime : Sunshine hours	4	298	74	2.41E+01	<0.0001
Daytime : Room	4	1761	440	1.43E+02	<0.0001
Daytime : dwelling number	48	42 283	881	2.86E+02	<0.0001
Weekday : Outdoor temp	1	148	148	4.80E+01	<0.0001
Weekday : Wind speed	1	174	174	5.64E+01	<0.0001
Weekday : Solar radiation	1	724	724	2.35E+02	<0.0001
Weekday : sunshine hours	1	317	317	1.03E+02	<0.0001
Weekday : dwelling number	12	2042	170	5.52E+01	<0.0001
Outdoor temp : Wind speed	1	146	146	4.74E+01	<0.0001
Outdoor temp : Solar radiation	1	1047	1047	3.39E+02	<0.0001
Outdoor temp : sunshine hours	1	2526	2526	8.19E+02	<0.0001
Outdoor temp : Room	1	55 574	55 574	1.80E+04	<0.0001
Outdoor temp : dwelling number	12	252 679	21 057	6.83E+03	<0.0001
Wind speed: solar radiation	1	673	673	2.18E+02	<0.0001
Wind speed: sunshine hours	1	713	713	2.31E+02	<0.0001
Wind speed : Room	1	231	231	7.48E+01	<0.0001
Wind speed : dwelling number	12	14 580	1215	3.94E+02	<0.0001
Solar radiation : Room	1	1981	1981	6.42E+02	<0.0001
Solar radiation : dwelling number	12	11 620	968	3.14E+02	<0.0001
Sunshine hours : Room	1	1770	1770	5.74E+02	<0.0001
Sunshine hours : dwelling number	12	21 426	1786	5.79E+02	<0.0001
Room : dwelling number	8	964 726	120 591	3.91E+04	<0.0001

Table 6

variables	time of day	unit	coefficients	magnitude
Intercept during workdays	morning	-	23.76	-
	day		24.82	
	evening		23.99	
	night		23.29	
Intercept during weekends	morning	-	23.80	-
	day		24.86	
	evening		24.02	
	night		23.32	
CO_2 concentration	-	ppm	0.00048	0.8
Outdoor temperature	morning	°C	-0.30	-12.5
	day		-0.32	
	evening		-0.33	
	night		-0.31	
wind speed during workdays	morning	m/s	-0.08	-2.6
	day		-0.20	
	evening		-0.06	
	night		0.02	
wind speed during weekends	morning	m/s	-0.01	-1.7
	day		-0.13	
	evening		0.01	
	night		0.09	
outdoor relative humidity	-	%	-0.063	-4.4
Solar radiation	-	W/m²	-0.0006	-0.6

Table captions

Table 1: description of dwellings and residences

Table 2: Results of the first statistical analyses of the probability of opening and closing windows. All significant terms included.

Table 3: Results of the analyses of the probabilities of opening and closing windows, with reduced number of interaction terms. The magnitude is a measure of the impact of the variable on the probability. It was calculated as the largest coefficient of the variable multiplied by the scale of the variable.

Table 4: Model of the window opening angle of the three top-hung windows.

Table 5: Analysis of variance for the linear regression model of trv set-point. All non-significant terms were removed from the full model by backward selection. The R^2 for the model was 0.86

Table 6: Results of the less complex model of the trv set-point with few interaction terms. The R^2 for the model was 0.31

Formulas

$$\log\left(\frac{\mathrm{p}}{1-\mathrm{p}}\right) = \mathrm{a} + \mathrm{b}_1 \cdot \mathrm{x}_1 + \mathrm{b}_2 \cdot \mathrm{x}_2 + \cdots + \mathrm{b}_\mathrm{n} \cdot \mathrm{x}_\mathrm{n} \qquad (1)$$

$$log\left(\frac{p}{1-p}\right) = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \cdots + b_n \cdot x_n + c_{12} \cdot x_1 \cdot x_2 + c_{13} \cdot x_1 \cdot x_3 + \cdots \qquad (2)$$

Where,
p is the probability of an opening/closing event
a is the intercept
$b_{1\text{-}n}$ are coefficients
$x_{1\text{-}n}$ are variables such as temperature, CO_2 concentration etc.
$c_{1\text{-}n1\text{-}1}$ are coefficients in the interaction terms

PAPER III

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Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions

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ABSTRACT

Based on building energy and indoor environment simulations, this study uses a recently developed method relying on Bayesian Network theory to estimate and compare the consequences for occupant performance and energy consumption of applying temperature criteria set according to the adaptive model of thermal comfort and the more conventional PMV model. Simulations were carried out for an example building with two configurations (with and without mechanical cooling) located in tropical, subtropical, and temperate climate regions. Even though indoor temperatures differed significantly between building configurations, especially in the tropical climate, the estimated performance differed only modestly between configurations. However, energy consumption was always lower in buildings without mechanical cooling, particularly so in the tropical climate.

The findings indicate that determining acceptable indoor thermal environments with the adaptive comfort model may result in significant energy savings and at the same time will not have large consequences for the mental performance of occupants.

1. Introduction

Conventional methods of determining acceptable indoor thermal conditions have been based mostly on human heat transfer models coupled with the estimation of psycho-physical, group-average indices of thermal sensation and comfort (e.g. Refs. [2,4,14]). Probably, the best-known and most widely used model is the PMV model, which was developed with human subjects exposed to well-controlled environments in climate chambers [11]. The PMV model has been validated in a wide range of studies in the field, probably most comprehensively in ASHRAE's worldwide research in buildings with HVAC systems that were situated in cold, temperate and warm climates and were studied during both summer and winter [5,9,10,18].

de Dear and Brager [8] argued that the PMV model inappropriately regarded building occupants as passive recipients of their indoor environment exposure and suggested that occupants should be allowed to be active in modifying their indoor environment as they preferred. They proposed an optional method to determine acceptable indoor thermal conditions, also known as the adaptive model of thermal comfort, which is a regression equation that relates the neutral temperature indoors to the monthly average temperature outdoors. The adaptive model has been included in recent versions of ASHRAE Standard 55 and EN 15251 for buildings with spaces without mechanical cooling, where the thermal conditions are controlled primarily by the occupants through opening and closing of windows [2,3].

Application of the adaptive model of thermal comfort in warm climate regions may result in relaxed temperature criteria and may therefore provide a potential means to reduce the consumption of energy used to cool buildings. One of the main themes of the discussion that rose at the introduction of the adaptive model was if it would also provide an acceptable degree of occupant satisfaction in spaces without mechanical cooling. It is likely that occupants in such spaces are used to larger temperature variation and therefore have lower expectations and would judge a given warm environment as less severe and less unacceptable than would people who are used to stricter climate control [12]. In the discussion, however, the effect of relaxed temperature criteria on occupant performance to some degree was sidestepped, possibly because no obvious approach was available to estimate the effects on occupant performance of indoor temperatures.

Jensen et al. [17] proposed a technique to assess the effects of the thermal indoor environment on the mental performance of office employees and to compare the economic consequences of different building designs based on occupant performance and

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energy use. The approach combines Bayesian network theory with dynamic simulation of the indoor environment and of the energy consumption as well as with dose–response relationships between indoor climate parameters and mental performance. The Bayesian network is based on the compilation of subjective thermal sensation data and the associated objective thermal measurements from 8,100 occupants of climate controlled buildings and 4,700 equivalent data records from buildings without mechanical cooling located in different parts of the world [7]. In the current study the technique is used to estimate and compare the consequences for occupant performance and energy consumption of applying temperature criteria defined by the conventional method (PMV) and the adaptive comfort model in an example building with and without mechanical cooling located in tropical, subtropical, and temperate climate regions.

2. Methods

Input to the assessment of employee performance was hourly values of operative temperature simulated for a space in a building with and without mechanical cooling, located in Singapore (tropical – latitude 1°14′ N), Sydney (subtropical – latitude 34°0′ S), San Francisco (temperate – latitude 37°47′ N), and Copenhagen (temperate – latitude 55°40′ N). Based on observations recorded in thermal comfort field studies in the two building configurations, a Bayesian network was used to infer the probability of the occupants being satisfied with the thermal conditions [17]. Since occupants in non-mechanically cooled buildings may be more forgiving of a warm environment than would people who are used to air-conditioning, different thermal sensation distributions would result from identical temperatures in the two building configurations. This is illustrated in Fig. 1, which is based on data from de Dear [7]. The distributions of thermal sensation votes cast by occupants in buildings with and without mechanical cooling at 22 °C follow an almost perfect Gaussian distribution, although without mechanical cooling the prevalence of warmer votes was somewhat higher. At 27 °C the distribution in buildings with mechanical cooling was left-skewed and almost 50% of the occupants in these buildings voted warm or hot, whereas more than 80% of the occupants in buildings without mechanical cooling at the same temperature voted slightly cool, neutral or warm.

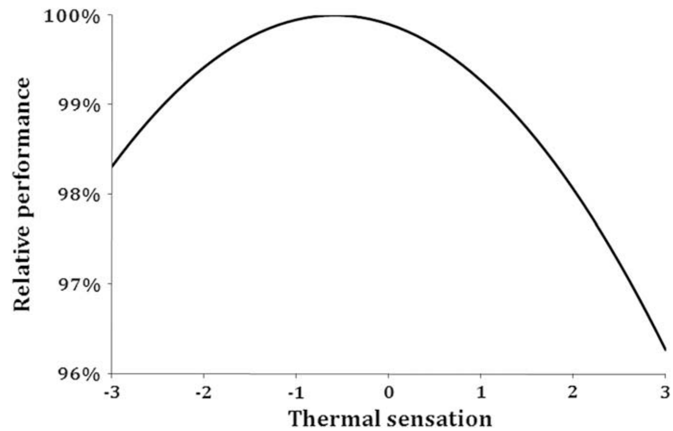

Fig. 2. Dose–response relationship between thermal sensation and mental performance.

As suggested in several earlier studies, thermal sensation for people in near thermal comfort conditions is more likely to influence performance than temperature *per se* (e.g. Refs. [20,21]). Using thermal sensation to quantify effects on performance of the thermal climate, the different distributions of thermal sensation votes will affect the outcome, whereas temperature as input would yield identical performance estimates at identical temperature levels.

Simulated hourly temperatures were thus used to estimate the thermal sensation distribution with and without mechanical cooling and, for both populations, to subsequently estimate mental

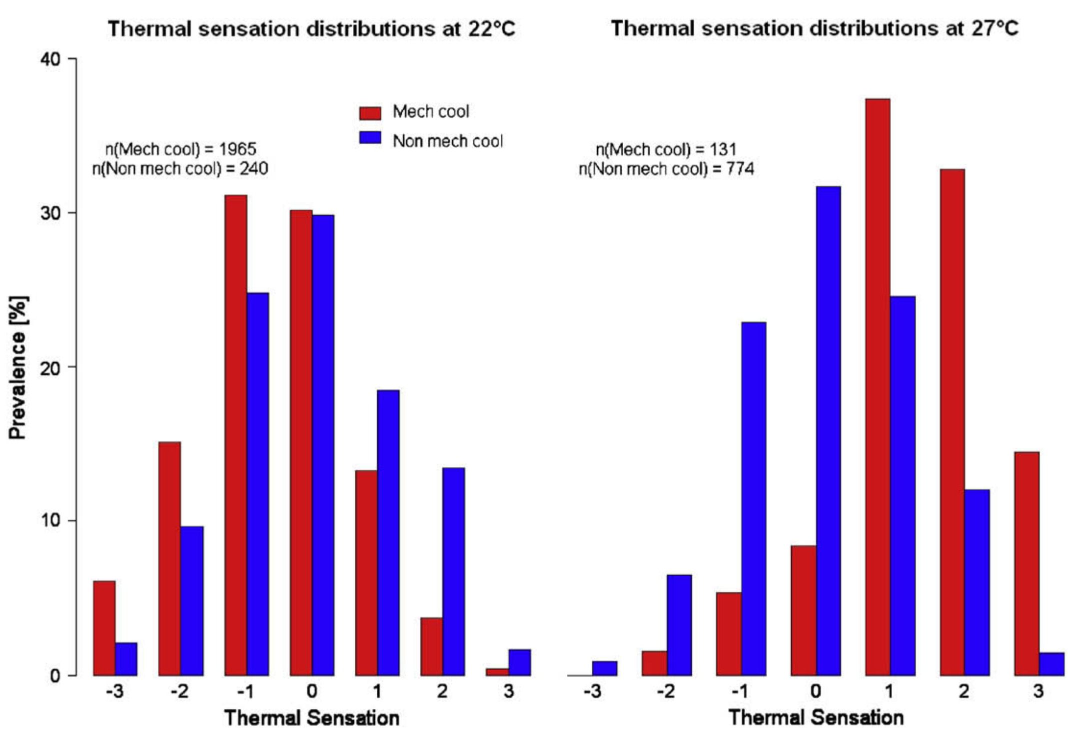

Fig. 1. Distribution of thermal sensation votes cast in buildings with and without mechanical cooling at recorded temperatures 22 °C and 27 °C. Data adopted from de Dear [7].

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Table 1
Monthly 24 h average temperature at Singapore Paya Lebar Airport, Sydney Int'l Airport, San Francisco Int'l Airport, Copenhagen Kastrup Airport and the temperature at 6 a.m. averaged for each month in Singapore, Sydney, San Francisco, and Copenhagen. Monthly averages adopted from www.worldclimate.com and values at 6 a.m. from Ref. [15].

Month	Singapore		Sydney		San Francisco		Copenhagen	
	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)
Jan	26.2	27.8	22.1	19.3	9.2	5.7	0.1	1.4
Feb	26.9	26.9	22.0	20.6	11.2	8.5	0.1	−0.6
Mar	27.3	28.3	20.9	18.5	11.8	8.1	2.3	1.7
April	27.7	29.2	18.3	15.0	13.1	8.9	6.5	4.6
May	27.7	28.8	15.2	12.9	14.5	10.2	11.6	9.9
June	27.5	28.6	12.8	10.1	16.3	12.2	15.2	13.0
July	27.2	26.9	11.8	8.7	17.0	13.3	16.8	15.0
August	27.1	29.0	13.0	9.2	17.6	12.6	16.3	15.3
September	27.1	27.3	15.2	11.7	18.0	13.1	13.3	11.0
October	27.2	29.9	17.6	14.8	16.1	12.3	10.0	8.6
November	26.8	25.8	19.4	16.7	12.6	9.7	5.3	4.5
December	26.3	25.4	21.2	18.5	9.6	7.3	1.4	1.0

performance by weighting the performance decrement according to the associated distribution of thermal sensation votes, using the dose–response relationship between thermal sensation and performance shown in Fig. 2. The dose–response relationship in Fig. 2 is a modification of the dose–response relationship suggested in Jensen and Toftum [16].

An alternative means of off-setting elevated temperatures may be to raise local air velocity to increase the cooling effect and maintain thermal comfort. This may result in reduced consumption of energy by the central air-conditioning, but currently requires individual control of the local air velocity by each occupant [2]. However, this study focused on low air velocities, which also were most prevalent in the ASHRAE field studies ($\leq$0.1 m/s). The matrix of conditions of this study compares temperature criteria determined according to the ASHRAE Standard 55 comfort envelope ($-0.5 < \text{PMV} < 0.5$) and according to the adaptive model of thermal comfort.

For the selected geographical locations, Table 1 illustrates monthly average outdoor temperature and the outdoor temperature at 6 a.m. averaged for each month during a normal year. The transition in clothing insulation from winter to summer and vice versa is naturally integrated in the adaptive model, but the conventional comfort envelope encompasses only two levels of clothing insulation corresponding to a distinct winter and summer situation (1.0 clo and 0.5 clo, respectively). The operative temperature limits for intermediate values of clothing insulation may be determined by linear interpolation between the limits for 0.5 clo and 1.0 clo, according to the following relationships [2]:

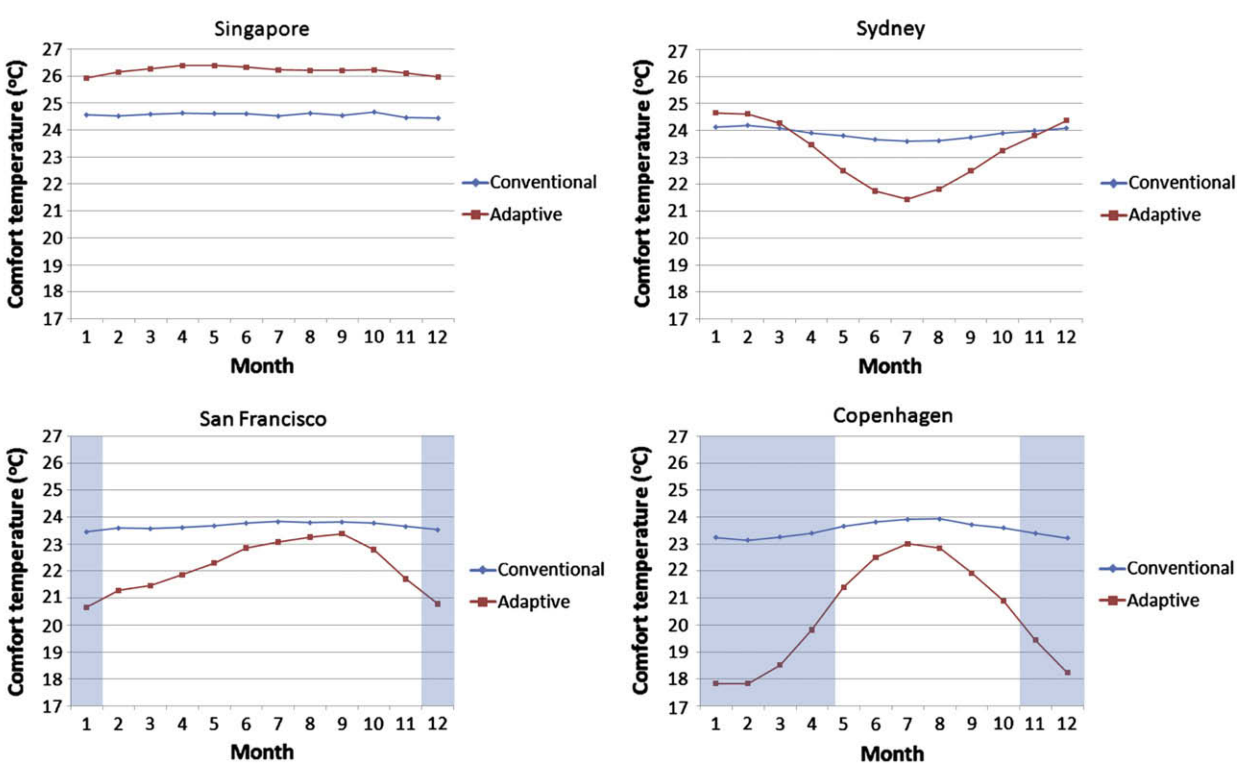

Fig. 3. Comparison of comfort temperatures determined according to the conventional method, adjusted for seasonal variation in clothing insulation, and the adaptive model at the four studied locations. Shaded regions show when the monthly average outdoor temperature was below 10 °C.

Table 2
Specifications of the simulated building.

Internal heat gain from equipment	1200 W
Number of occupants	10
U-value of external wall	0.708 W/(m^2 K)
Type of windows	2-layer window with 15 mm air gap and wooden frame (10% of window area)
Center U-value of glazing in window	2.8 W/(m^2 K)
Solar heat gain coefficient of window	0.76
U-value of window frame	2.0 W/(m^2 K)
Size of window	1.25 m × 1.20 m
Number of windows	6
Dimensions of the room	10 m × 12 m

$$t_{\min,I_{cl}} = \left[(I_{cl} - 0.5\ \text{clo})t_{\min,1\text{clo}} + (1.0\ \text{clo} - I_{cl})t_{\min,0.5\text{clo}}\right]/0.5\ \text{clo}(^{\circ}\text{C}) \quad (1)$$

$$t_{\max,I_{cl}} = \left[(I_{cl} - 0.5\ \text{clo})t_{\max,1\text{clo}} + (1.0\ \text{clo} - I_{cl})t_{\max,0.5\text{clo}}\right]/0.5\ \text{clo}(^{\circ}\text{C}) \quad (2)$$

in which $t_{\max,I_{cl}}$, upper operative temperature limit for clothing insulation I_{cl}; $t_{\min,I_{cl}}$, lower operative temperature limit for clothing insulation I_{cl}; I_{cl}, thermal insulation of the clothing in question (clo).

From the comfort envelopes specified in ASHRAE standard 55 Fig. 5.2.1.1 (Ref. [2]), the following temperature limits for 0.5 clo and 1 clo were obtained, corresponding to PMV = ±0.5 and PPD = 10%:

$$t_{\min,1\ \text{clo}} = 20\ ^{\circ}\text{C}$$

$$t_{\max,1\text{clo}} = 24\ ^{\circ}\text{C}$$

$$t_{\min,0.5\text{clo}} = 23\ ^{\circ}\text{C}$$

$$t_{\max,0.5\text{clo}} = 26\ ^{\circ}\text{C}$$

These values are within the comfort envelope and are also in agreement with temperature limits specified in refs. [14] and [3] for winter (1.0 clo) and summer conditions (0.5 clo).

With data from the same database that was used to develop the adaptive comfort model, De Carli et al. [6] analyzed matching observations of clothing insulation and external temperature and identified the outdoor temperature at 6 a.m. to be the variable that correlated best with clothing insulation in buildings without mechanical cooling (among the four tested variables). In buildings with mechanical cooling, the correlation did not differ between the outdoor temperature at 6 a.m., mean daily temperature or mean monthly temperature. The study by De Carli et al. [6] suggested a set of regression equations to estimate mean occupant clothing insulation based on the outdoor temperature at 6 a.m.:

With mechanical cooling:

$$I_{cl} = 0.766 - 0.01 \cdot t_{\text{outdoor, 6a.m.}}(\text{clo}) \quad (3)$$

Without mechanical cooling:

$$I_{cl} = 0.980 - 0.02 \cdot t_{\text{outdoor,6a.m.}}(\text{clo}) \quad (4)$$

In the current study, Eq. (3) applying to buildings with mechanical cooling was used to estimate the average clothing insulation during the year in such buildings.

In buildings without mechanical cooling, comfort temperature and the corresponding upper and lower temperature limits corresponding to 90% satisfied were determined from the monthly average temperature using the following equations [8]:

$$T_{\text{lower}} = 15.3 + 0.31 \cdot t_{\text{outdoor, monthly average}}$$

$$T_{\text{comfort}} = 17.8 + 0.31 \cdot t_{\text{outdoor, monthly average}}$$

$$T_{\text{upper}} = 20.3 + 0.31 \cdot t_{\text{outdoor, monthly average}}$$

Based on the monthly average temperature recorded at 6 a.m., Eq. (3) was first used to determine the monthly average clothing insulation and then Eqs. (1) and (2) were used to determine the upper and lower limit of the temperature comfort envelope. Next, the comfort temperature adjusted for the seasonal variation in clothing insulation was determined as the average of the upper and lower temperature limit. For each studied location, Fig. 3 compares comfort temperature determined according to the conventional method, adjusted for the variation in clothing insulation due to outdoor temperature, with comfort temperature determined according to the adaptive model.

In ASHRAE 55, the adaptive model has a lower outdoor cut-off temperature at 10 °C, below which the allowable operative temperature limit should not be used and where no indoor temperature for naturally conditioned buildings is specified [2]. In Copenhagen, the monthly average outdoor temperature was below this cut-off temperature from November to April and in San Francisco in December and January. During these periods, a comfort temperature corresponding to an outdoor temperature of 10 °C was used ($t_{\text{comfort}} = 20.9$ °C).

2.1. Indoor climate and energy simulations

In order to estimate hourly indoor temperatures and energy data, simulations were carried out using the software IDA ICE version 3.0 build 16 [13]. The same building setup was used at all four locations with only minor changes between locations. A single room of 120 m^2 occupied by 10 persons was simulated with the specifications listed in Table 2.

The simulated office was adjacent to other rooms with identical thermal conditions, i.e. the three internal walls were adiabatic. Also, the temperature conditions above and below the office were symmetrical resulting in the heat being transmitted through the ceiling was re-transmitted through the floor. Thus, the ceiling of the simulated office acted as the floor of the office located on the level above and the floor of the simulated office acted as the ceiling of the office below. Heating was provided by waterborne radiators (Fig. 4).

The internal heat gain from electrical equipment (PCs, etc.) was 50% of the total gain (Table 2) from midnight to 7 a.m. and from 6 p.m. to midnight. During office hours from 9 a.m. to 4 p.m. it was 100% and from 7 a.m. to 9 a.m. and again from 4 p.m. to 6 p.m. it was linearly increased and decreased, respectively, between 50% and 100%. The occupant load was 100% from 9 a.m. to 11 a.m. and again from 1 p.m. to 4 p.m. From 6 p.m. to 7 a.m. it was 0% and was increased linearly from 7 a.m. to 9 a.m. and decreased from 4 p.m. to 6 p.m. During lunch (11 a.m. to 1 p.m.), the occupancy was decreased linearly to 50% at 12 p.m. and then increased again. The lighting was controlled automatically to be on when a desktop in the middle of the office was lit by daylight at 100 lux or less and off when the daylight illumination exceeded 10,000 lux.

All windows were equipped with a stationary overhang of 0.75 m tilted approximately 35° from horizontal and located approximately 0.3 m above the upper edge of the window. In San Francisco the overhang was extended to 1 m width. The overhang extended the full width of the building.

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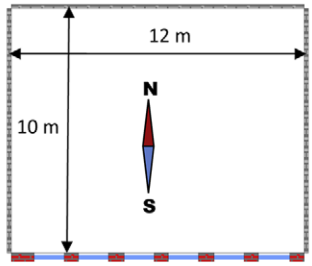

Fig. 4. The office seen from above (left) and the external wall seen from the inside (right). The external wall was facing south when the building was located in the northern hemisphere and facing north in the southern hemisphere.

2.2. Simulated temperature control

In the naturally ventilated building, the occupants by behavioural means attempted to maintain the temperature within the upper and lower temperature limits and the temperature was controlled by adjusting the window opening and the radiators. The windows were opened when the indoor temperature exceeded the upper temperature limit and they were closed again when the temperature was below the lower temperature limit. The total aerodynamic opening area with all windows 100% open was set to 4.5 m^2. The opening area was set at the time of the window opening event and did not change until the windows were closed again. If the outdoor temperature at the time of the opening exceeded 25 °C, the windows were opened 100%. If the outdoor temperature at the time of the opening event was lower than 5 °C, the windows were opened only 20%. Between 5 °C and 20 °C, linear interpolation was used to determine the opening area of the windows.

Leaks and cracks in the building envelope were positioned in all four external walls in the building and connected to the room. The size and position of the leaks were adjusted so that the annual average infiltration rate was 0.1 h^{-1}.

The flow of water through the radiator was regulated with a p-controller. If the indoor temperature dropped more than 1 °C below the limit, the flow through the heater was 100%. The supply temperature of the water varied with the outdoor temperature.

In the mechanically ventilated buildings, the indoor temperature set-point was determined by the clothing insulation value according to Eqs. (1) and (2). The temperature was adjusted by the heating and cooling coils in the ventilation system and by a waterborne radiator, which was controlled as described for the naturally ventilated buildings. The supply air temperature was regulated in the range of 8 °C and 1 °C below the indoor temperature.

In order to save energy, the fan speed was reduced to 20% after working hours and the outdoor air supply rate was decreased during the cold periods of the year as shown in Table 3. At all locations, the maximum power output of the cooling coil was adjusted so the annual number of hours with indoor temperatures higher than the upper limit was between 90 and 110 h during occupancy.

2.3. Performance calculations

To calculate the effects on performance of the temperature exposure, the hourly temperatures simulated in IDA for each location and building configuration were imported into a MATLAB procedure, which implemented the Bayesian Network (BN) model suggested by Jensen et al. [17]. The BN is a graphical model that represents the links between indoor climate variables and characterizes their correlation. In the present model, temperature and building configuration were input to the BN. The indoor temperature affects multiple variables at the same time, including activity, clothing level, and thermal sensation, while the building configuration affects for example air velocity and thermal sensation. Most of these indoor climate variables are inter-correlated and therefore difficult to estimate in a deterministic model.

The BN handles such correlation by using probability distributions in the calculations. Each variable is divided into intervals (states), which are attributed a probability (e.g. the variable clothing has three states: light, normal and heavy clothing. Given that the temperature is high, the probability of the occupants wearing light clothing is higher than them wearing heavy clothing).

The data underlying the conditional probabilities were adopted from de Dear [7]. Knowledge of the state of a variable (e.g. the temperature is 30 °C in a building with mechanical cooling) enables the BN to infer the states of other variables by the probabilistic calculations. This yields a probability distribution of the states (e.g. probability of occupants wearing light clothing: 90%, probability of people wearing normal clothing: 8% and probability of people wearing heavy clothing 2%) and adds an uncertainty to the model estimate (we are not 100% sure that all people will wear light clothing, we are 90% sure), which can be considered to be a better representation of the real world situation.

In real offices, the occupants are affected differently when exposed to the same IEQ conditions as illustrated in Fig. 1. The

Table 3
Settings and schedule for operation of the ventilation system in the buildings with mechanical cooling.

Location	Singapore	Sydney	San Francisco	Copenhagen
Fan running at reduced speed	Weekends and workdays between 6 p.m. and 2 a.m.	Weekends and workdays between 6 p.m. and 5 a.m.	Weekends and workdays between 6 p.m. and 2 a.m. from October to May	Weekends and workdays between 6 p.m. and 5 a.m. from October to May
Recirculation/heat recovery	Modulated between 0 l/s and 400 l/s recirculation.	Modulated between 0 l/s and 400 l/s recirculation.	Heat recovery unit. Efficiency between 0% and 60%	Heat recovery unit. Efficiency between 0% and 60%
Outdoor air supply rate	70 l/s	70 l/s	200 l/s from May to September. 400 l/s rest of year	200 l/s from May to November. 300 l/s rest of year
Cooling coil max power output	5400 W	4000 W	2500 W	750 W

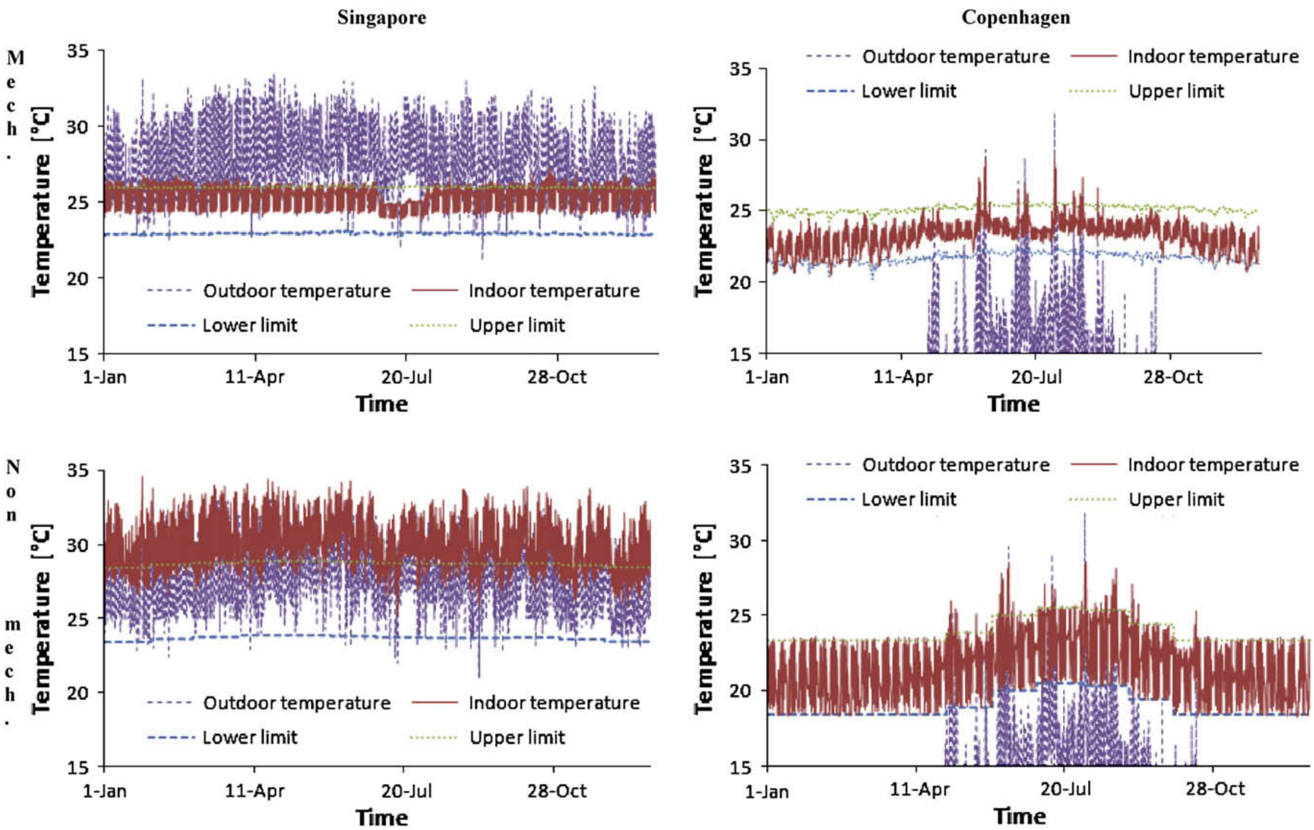

Fig. 5. Simulated indoor temperature profile, outdoor temperature and upper and lower comfort temperature limits in the buildings in Singapore and Copenhagen. Upper figures: With mechanical cooling; lower figures: Without mechanical cooling.

suggested performance model uses the BN to estimate the difference between people's thermal sensation, which not only depends on the temperature exposure, but also on the building configuration. With the dose–response relationship shown in Fig. 2, the model estimated a performance index indicating an accumulated relative performance measure, where 100% was considered to be optimal performance and, e.g. 98% corresponded to a 2% decrement in performance due to the thermal conditions during the period in question. Mathematically, the calculation of the relative performance can be expressed as shown in the equation below:

$$\Pi = \sum_i w \cdot BN(\mathrm{temp}_i) \quad \text{for } i = 1, 2, \ldots, n$$

in which, Π is the performance index in percent, i is the time segment for which the performance is calculated (e.g. working hours during a year), w is a weighting factor for each time segment ($w = 1/i$), temp_i is the temperature in time segment i, and $BN(\mathrm{temp}_i)$ is the performance output from the Bayesian Network as a function of temp_i.

3. Results

For the two climatic extremes included in this study (Singapore and Copenhagen), Fig. 5 shows the simulated indoor temperature profiles during a year in the two building configurations and the corresponding temperature comfort ranges, determined according to the adaptive model and the PMV model with adjustments for clothing. In the building without mechanical cooling located in Singapore, the indoor temperature during most of the simulated period was well above the upper comfort temperature, even though the adaptive model yielded far more relaxed temperature criteria as compared with the PMV model used in the buildings with mechanical cooling. In the building with mechanical cooling in Singapore, the temperature rose during the day and exceeded by a small amount the upper comfort temperature almost daily. In Copenhagen, this exceedence was limited to a few extreme days per year.

Table 4 summarizes the accumulated number of occupied hours during the simulated year when the indoor temperature exceeded the upper comfort temperature. In correspondence with Fig. 5, the building without mechanical cooling in Singapore stood out with nearly 100% of the hours during occupancy above the temperature limit. However, also in Sydney, San Francisco, and Copenhagen the

Table 4
Accumulated number of hours when the indoor temperature exceeded the upper comfort limit and percent of the occupied hours when the temperature fell in the ranges <22 °C, 22–26 °C, and >26 °C.

	Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling				
Accumulated hours (h)[a]	2169	756	250	232
% of hours with $t < 22$ °C[b]	0	12.6	30.2	41.6
% of hours with $t \in$ 22–26 °C[b]	0	52.1	62.7	53.6
% of hours with $t > 26$ °C[b]	100	35.3	7.1	4.8
With mechanical cooling				
Accumulated hours (h)[a]	103	93	99	98
% of hours with $t < 22$ °C[b]	0	0	0	0.8
% of hours with $t \in$ 22 – 26 °C[b]	87.6	95.2	97.1	96.1
% of hours with $t > 26$ °C[b]	12.4	4.8	2.9	3.1

[a] Accumulated number of hours during occupancy with temperatures above the upper comfort limit.
[b] Percent of the occupied hours when the temperature fell in the given range.

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Table 5
Energy output from the indoor climate and energy simulations.

Location	Singapore		Sydney		San Francisco		Copenhagen	
Ventilation	With mechanical cooling	Without mechanical cooling	With mechanical cooling	Without mechanical cooling	With mechanical cooling	Without mechanical cooling	With mechanical cooling	Without mechanical cooling
Heating [kWh]	0	0	984	6	2115	17	5521	86
Cooling [kWh]	31,226	0	6033	0	772	0	301	0
Electrical [kWh]	9752	8279	9755	8236	10,957	8259	10,395	8291

indoor temperature in the buildings without mechanical cooling periodically was too high. In the buildings with mechanical cooling, the simulations were tuned to yield exceedence of comparable magnitude, around 100 h per year.

Table 5 shows the energy consumption resulting from the simulations, distributed on heating, cooling and electrical consumption. Cooling and heating contributions are consumption of cooling and heating in the coils in the HVAC system and the radiators, not primary energy consumption. In the mechanically cooled buildings, the electrical contribution includes the fan energy consumption in addition to lighting, circulation pumps and equipment. Not surprisingly, the energy penalty for maintaining the temperature within the comfort range was very high in Singapore, and to a much lesser degree in Sydney, whereas in San Francisco and Copenhagen application of the mechanical cooling rarely was necessary. However, in the two latter cities, the heating energy consumption was significantly higher than with mechanical cooling (HVAC system) due to the higher air exchange rate also during the winter season. As reflected in the low heating energy consumption without mechanical cooling, the simulated building configuration resulted in low transmission heat loss due to the adiabatic internal walls and the small area of the well-insulated external wall. At all simulated locations, the energy consumption was significantly lower in buildings without mechanical cooling.

With the simulated temperature profiles as input, the BN was used to determine annual average performance indices at all locations and in both building configurations. The resulting indices are shown in Table 6. In general, the annual performance index varied only little across location and building configuration, despite the considerable differences in the simulated indoor temperatures. Perhaps most surprising was the result from Singapore, where the simulated temperature without mechanical cooling continuously was higher than even the relaxed temperature criteria determined with the adaptive model, but where the performance index was 98.9 and 98.1 in buildings with and without mechanical cooling, respectively. Yet, of all the simulated locations the lowest performance was observed in Singapore in the building without mechanical cooling. In Sydney, San Francisco and Copenhagen there was only negligible difference between the performance indices with the two building configurations. Also, the mean temperature differed much less between building configurations at these locations than in Singapore.

4. Discussion

It was a surprise that the rather extreme difference in temperature between buildings with and without mechanical cooling resulted in so modest differences in the performance estimates. Especially in Singapore, where the difference in mean temperature between the two building configurations during the occupied hours was as high as 5.9 °C, the decrement in the estimated performance was only 0.8%-points. Several factors contributed to this result: One important influencing factor was the two different thermal sensation distributions that were used in the BN to estimate performance, one for buildings with mechanical cooling and one for buildings without. As was the basis for the adaptive model to recommend relaxed temperature criteria, occupants in buildings without mechanical cooling, who were not used to strict climate control, were more forgiving of their thermal exposure and cast less extreme votes on the thermal sensation scale at high temperatures as is also illustrated in Fig. 1 [8,12]. Thus, when thermal sensation, rather than temperature, is used as input to the estimation of performance, the effect of high temperatures is moderated because the proportion of occupants who feel neutral or slightly warm rather than warm or hot will be much higher in buildings without mechanical cooling, despite the high temperatures. Seppänen and Fisk [19] suggested a dose-response relationship between temperature and performance, which, if used in this study, would have yielded quite different results, since it would not have been possible to account for differences in thermal sensitivity and thus distinguish the populations in buildings with and without mechanical cooling. With their dose-response relationship, the high indoor temperatures observed during extended periods of the year in some of the simulated buildings and locations would result in much larger performance decrements as a consequence of the temperature exposure. We believe that thermal sensation, rather than temperature, is more representative of the exposure and thus a better variable for prediction of thermal effects on performance, as has also been suggested in several earlier, experimental studies (e.g. Refs. [20,21]). The difference in thermal sensation distributions at identical temperature exposures between the populations of the two building configurations was crucial to the development of the adaptive model as it was to the initiation and the outcome of the current study. As it turned out, this difference, at least partly, also explained why the difference in performance was smaller than anticipated with the considerable differences in environmental exposure.

Another influencing factor was the applied dose-response relationship (Fig. 2), which was developed by combining the results of several laboratory studies on thermal exposure and mental performance (studies listed in Ref. [16]). Most of the exposures in these studies focused on the in- and near-comfort temperature ranges and no exposure took place at temperatures above 28 °C, probably resulting in a "flatter" dose–response relationship than could be expected with more extreme experimental temperature exposures. Nevertheless, even though total building economy was considered beyond the scope of this study, expenses incurred in occupant salaries exceed by several magnitudes building operation and maintenance costs, and investment in improved indoor environment, resulting in even small improvements in performance, has been shown to be economically justifiable [16,17]. Thus, the basis of assessing thermal environment effects on performance

Table 6
Performance indices determined from one-year simulations of indoor temperature.

	Performance index (%)			
	Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling	98.1	98.8	99.0	99.0
With mechanical cooling	98.9	99.0	99.1	99.1

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should be extended to temperatures above 28 °C and incorporated in the dose–response relationship to fully address the exposures that resulted from the simulations.

Whereas the estimated performance index differed only modestly between building configurations, the energy consumption was always lower in buildings without mechanical cooling, especially in Singapore where the omission of mechanical cooling yielded a substantial reduction of the energy consumption. Based on the results of this simulation study it thus appears that determining acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of occupants who are more attentive to their thermoregulatory options and do not have high expectations to their indoor environment. In the warmer climate regions, the calculated energy savings for buildings without mechanical cooling may even be conservative compared with current air-conditioning design practice because the design comfort temperatures based on the PMV model may be higher than the actual design temperatures used in real buildings. In San Francisco and Copenhagen, inclusion of mechanical cooling had only negligible effect on the cooling energy consumption indicating that the periods when the cooling system was active were short. The number of hours when the temperature was below 22 °C in these two cities was much higher without than with mechanical cooling indicating a lower mean temperature in this building configuration during the heating season, although heating with both building configurations was controlled according to identical set-points.

Inarguably, an infinite number of scenarios could have been simulated, each with different energy and performance outcomes and each representing a compromise that restricts the generalisation of the study results. This study applied a rather crude approach with limited local modification and building features considered to be representative of a universal configuration with or without mechanical cooling and in which as many control and other input parameters as possible remained constant between cities. Indeed, the major difference in the simulated building configuration was the inclusion of an HVAC system. Nevertheless, to reach to a different conclusion as regards the performance index estimated in the two building configurations would require a radically different building configuration or that the building control system was specified and set up completely differently.

de Dear and Brager [8] pointed out that occupants in buildings without mechanical cooling to a higher degree rely on their behavioural opportunities to maintain an acceptable indoor environment than occupants who are used to automatic control systems. State-of-the-art of building simulation software allows only a rather mechanistic approach to the simulation of occupant control, e.g. windows are opened when the simulated temperature reaches a specified set-point rather than as a response to occupant perceptions. Indeed, Andersen et al. [1] showed that occupant behaviour could influence the consumption of energy to climatise a building by as much as 330%. The realism of a simulation study as this could be enhanced by the inclusion of probabilistic knowledge of occupant behaviour and subjective decisions in response to environmental exposures.

5. Conclusions

As a consequence of the different thermal sensation distributions observed in buildings with and without mechanical cooling, occupant performance was only slightly lower without mechanical cooling when thermal sensation was used as input to the estimation of performance, even in a tropical climate where simulated indoor temperatures were much higher than in buildings with mechanical cooling. However, consumption of energy to climatise the buildings without mechanical cooling was considerably lower without mechanical cooling indicating that determination of acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of the occupants.

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PAPER IV

Simulation of the Effects of Occupant Behaviour on Indoor Climate and Energy Consumption

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SUMMARY

In this study the influence of occupant behaviour on energy consumption were investigated in simulations of a single room occupied by one person. The simulated occupant could manipulate six controls, such as turning on or off the heat and adjusting clothing. All control actions were carried out with the aim of keeping the PMV value within predefined limits in accordance with CR1752 [1]. An energy consuming and an energy efficient behavioural mode were simulated. A reference simulation was made during which the occupant had no control over the environment.

The occupant was able to keep the thermal indoor environment close to neutral when he/she had the possibility to manipulate the controls. The energy consumption was similar within each behavioural mode regardless of the PMV limits. However, the energy consumption in the energy consuming behavioural mode was up to 330 % higher than in the energy efficient behavioural mode.

INTRODUCTION

Buildings account for more than 40 % of the energy consumption in the EU member states and households are responsible for consuming more than 26 % [2]. Consequently, reductions of the energy consumption in buildings are instrumental to the efforts of alleviating the EU energy import dependency and comply with the Kyoto Protocol.
Indeed, occupant behaviour influences the amount of energy consumed to sustain a comfortable indoor environment. However, the extent to which occupant behaviour affects building energy consumption is largely unknown. The purpose of this study was to investigate the extent of this influence. This paper describes simulations of a naïve and a rational behaving occupant. The naïve occupant controlled the indoor climate using an energy expensive behaviour, while the rational occupant controlled the indoor climate in an energy efficient way.

METHODS

The simulations were carried out using a dynamic building simulation software [3]. The model consisted of a single room (4 m x 7 m) with a single occupant seated in the middle of the room. The room had one exterior wall (facing south) with a window and a heater underneath it. The building was placed in a suburban environment in Copenhagen, Denmark. All simulations were annual simulations using the Danish Design Reference Year for Copenhagen.

The simulated occupant could manipulate four different controls to adjust the environment (table fan, window opening, blinds, and heating) and two controls by which the occupant could adjust to the environment (clothing insulation and metabolic rate). All control actions were carried out with the aim of keeping the PMV value within predefined limits. Two behavioural modes were simulated. In the behavioural mode 1, the indoor environment was controlled in an energy expensive manner (naïve occupant), while the controls were operated in an energy efficient way in behavioural mode 2 (rational occupant). In both behavioural modes, three limits for the PMV index were set in accordance with the guidelines in CR1752 (+/-0.2, +/-0.5 and +/-0.7 for quality categories A, B, and C, respectively) [1], resulting in a total of six simulations. A seventh reference simulation was made during which the occupant had no control over the environment. In this simulation the occupant only controlled the clothing insulation and the metabolic rate.

Table 1: Setup of the simulations.

Criteria	Behavioural mode 1	Behavioural mode 2
A (-0.2<PMV<0.2)	Simulation 1A	Simulation 2A
B (-0.5<PMV<0.5)	Simulation 1B	Simulation 2B
C (-0.7<PMV<0.7)	Simulation 1C	Simulation 2C

In each simulation, all control actions were used to maintain PMV within the predefined limits. An example of the two behavioural modes for criterion A is given in Figure 1. Here it is seen that in behavioural mode 1, at increasing PMV, the table fan was turned on at PMV=0.03. If that did not stop the increase in PMV, the window was opened at PMV=0.06, blinds drawn at PMV=0.09, a clothing garment was removed at PMV= 0.11 and the metabolic rate was decreased to 1 met when PMV was higher that 0.14. Finally the heating was turned off when the PMV value increased beyond 0.17. When the PMV decreased below 0, the heating was turned on, the metabolic rate and clo value was increased, blinds opened, window closed and the fan was turned off, in that specific order.
In behavioural mode 2, the order of controls was inverted so the occupant turned off the heat as the first thing, when feeling warm – instead of turning on the fan.
In simulations B and C, the sequence of control actions at increasing or decreasing PMV were unchanged but the PMV value at which a control action was taken was increased according to the +/- 0.5 and +/- 0.7 criterion.

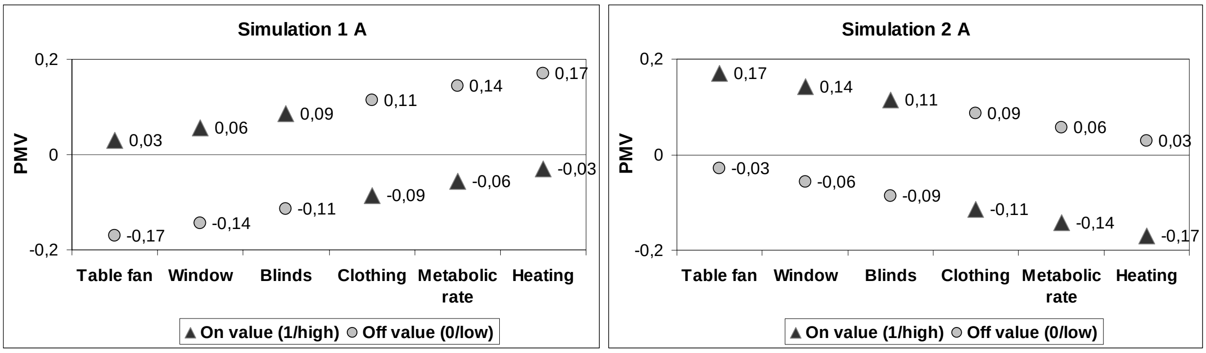

Figure 1: The control scheme for the energy consuming and the energy saving Behavioural modes for criterion A.

The occupant was constantly present in the room and was sleeping from 22:30 till 6:00 in the morning. During weekends the occupant slept from 24:00 till 8:00. During the sleeping periods the on and off values for the controls that adjusted the environment were multiplied by two to simulate that it takes a higher level of discomfort to act while sleeping than while being awake. The control of clothing and metabolic rate during the night is described below.

Table fan: When the fan was turned on the air speed at the occupant was increased by 1 m/s and the electric power consumption was increased by 50 W. These values were based on measurements using a normal table fan and a hot sphere manometer. During the measurements an average increase in air speed of approximately 1 m/s was detected when the fan was pointed directly at the occupant at a distance of 3 m. When the fan was pointed slightly to one of the sides of the occupant an airflow increase of 0.25 m/s was measured. Due to numerical problems in A simulations, the air speed was only increased by 0.25 m/s in simulation 1A and 2A. The power was kept at 50 W.

Window: The aerodynamic size of the window opening (corresponding to the size of a sliding window) was set each time the window was opened and remained unchanged until the window was closed. The opening size of the window depended linearly on the air change rate in the time step previous to the opening event. An air change rate of 0 h^{-1} in the time step prior to the opening event lead to an opening size of 0.6 m² while an air change rate of 2 h^{-1} in the time step prior to an opening event lead to an opening size of 0.12 m². When the air change rate with closed window exceeded 2.5 h^{-1}, the window was not opened even though PMV exceeded the window opening control value.
This was chosen because the air change rate depended on the wind speed outside the building. When there was a strong wind the air change rate was high and the window opening was small when the window was opened. When there was no wind the air change rate was small and when the window was opened it was opened completely
When the window was open the air speed at the location of the occupant was increased by:

$$V_{air} = 0.2 \cdot \frac{Q \cdot Vol}{A_{opening} \cdot 3600} \qquad (1)$$

Where
V_{air} is the air velocity at the occupant [m/s], Q is the air change rate [h^{-1}], Vol is the volume of the room, $A_{opening}$ is the aerodynamic area of the window opening.
The fraction in equation 1 is the air speed in m/s in the opening. The factor of 0.2 is multiplied because the airspeed decreased as a function of the distance to the window opening.
When the window was closed and the fan was off the air speed at the location of the occupant was 0.1 m/s.

Blinds: The binds were on/off controlled. They were external blinds that reduced the solar heat gain coefficient by a factor of 0.14 and reduced the direct energy transmission (short wave) by a factor of 0.09. The blinds were closed every night.

Clothing: The clothing insulation of the occupant could assume two values (Hi and Low), which were set each day at 6 o’clock in the morning on the basis of the outdoor temperature. This was done to model the action of taking on or off a piece of clothing. Both the time of day when the clothing insulation values were determined and the clothing insulation values were modelled according to [3] in the area of natural ventilation. The clothing insulation values were calculated using the following relation:

$$Clo_{Hi} = -0.024 \cdot T + 1.1 \quad (2)$$
$$Clo_{Low} = -0.015 \cdot T + 0.83 \quad (3)$$

Where *Clo* is the insulation of the occupants clothing [Clo], *T* is the outdoor temperature at 6:00 in the morning [°C].
During the night the clothing value was regulated continuously between 1.0 Clo and 2.5 Clo depending linearly on the PMV value. This was done to model a blanket or duvet that can be taken on or off in small increments while sleeping.

Metabolic Rate: The metabolic rate depended linearly on the PMV value assuming 1.0 Met at the PMV=off control value and 1.3 Met at the PMV=on control value. The metabolic rate of the occupant was 0.8 Met while sleeping.

Heating: The heating system comprised a water based radiator and a boiler with an efficiency of 66 %. The supply temperature to the radiator was 65 °C at outdoor temperatures below -12 °C and 20 °C at outdoor temperatures above 17 °C. Between -12 °C and 17 °C the supply temperature varied linearly with the outdoor temperature. The water flow through the heater was either on or off.

Infiltration rate: The simulated building had two cracks at different heights in each exterior wall. All cracks connected the interior of the building to the exterior environment. The local wind pressure coefficient of the faces of the building was determined according to [5]. The opening area of the cracks was determined by running a simulation with closed window and aiming for an average infiltration rate of 0.25 h^{-1}. In a study from 1985 [6] the average infiltration rate in 14 Danish dwellings ventilated by natural ventilation was measured. In this study, an average value of 0.19 h^{-1} was obtained, but it is stated that the 14 dwellings were among the most tightly sealed in the Danish housing mass.

Lighting: When the occupant was awake, the electrical lighting was turned on when if the daylight level dropped below 150 lux on a horizontal surface 0.6 m above the floor level at the location of the occupant (in the middle of the room). The light was only turned off when the occupant went to sleep, resulting in the light being on for the entire day if it was turned on in the morning.

RESULTS AND DISCUSSION

As seen in figure 2, the PMV index was close to neutral for a very large part of the year in all the simulations with active occupant behaviour. For the reference case with passive behaviour the PMV was far from neutral in a large part of the year (below -1 or above 1 during 72% of the year).
The PMV index was similar in the simulations with active occupant behaviour and attained values outside the control criteria for only small parts of the year. This means that the occupant was successful in controlling the environment within the comfort criteria.

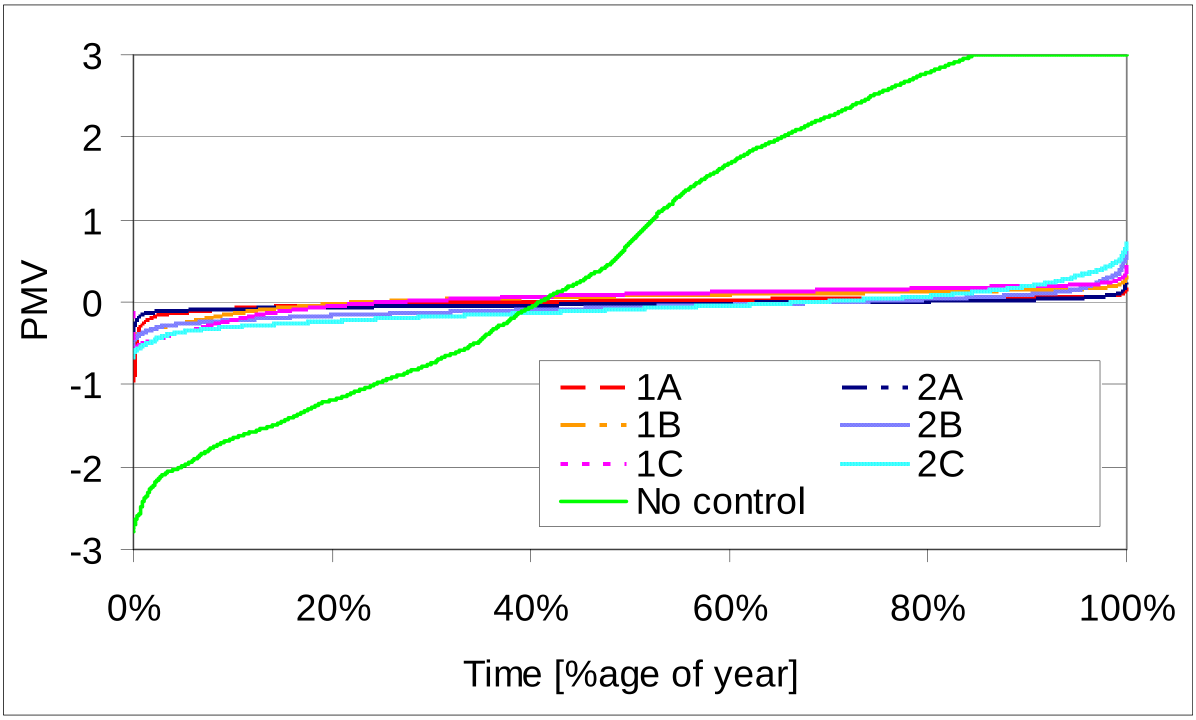

Figure 2: Duration curves for the PMV index in the 6 simulations and for the reference simulation. The figure shows how long time (in percentage of a year) the PMV index was below a certain value.

The total energy consumption refers to primary energy consumption. According to the Danish building code [7] this was calculated as the sum of all energy consumptions, where the electric consumptions were multiplied by 2.5. The highest primary energy consumption of 3948 kWh/year (simulation 1A) was 3.30 times higher than the lowest primary energy consumption of 1198 kWh/year (simulation 2C). Within each comfort control criteria the largest difference in primary energy consumption between the two behavioural modes was 324 % (3882 kWh/year simulation 1C was 3.24 times higher than 1198 kWh/year in simulation 2C). Within the two behavioural modes the largest difference in primary energy consumption was 117 % (1400 kWh/year in simulation 2A was 1.17 times higher than 1198 kWh/year in simulation 2C). This means that the comfort control criteria had much less impact on the primary energy consumption than the behavioural mode.

Table 1: Energy consumption in the simulations. The primary energy was calculated by multiplying electricity consumption by 2.5 according to the Danish building code. [7]

energy consumption pr. Year [kWh/year]	1A	1B	1C	2A	2B	2C	No control
Heating	2532	2372	2346	923	768	720	1812
Fan	380.1	423.6	431.0	1.4	0.3	0.1	0.0
Circulation Pump	13	13	13	3	2	2	13
Lighting	174	172	171	187	189	189	131
Primary energy for heating, ventilation and lighting	3948	3891	3882	1400	1246	1198	2171

Heating: The heating was turned on more often in Behavioural mode 1 than in Behavioural mode 2. Similarly, narrowing the control criteria resulted in higher energy consumption for heating.

Fan: A narrowing of the control criteria resulted in a decrease in the energy consumed by the fan in Behavioural mode 1. In Behavioural mode 2 this was opposite. In Behavioural mode 1 the fan was turned on as the first action when the occupant felt warm and turned off as the last control action when the occupant felt cold. In Behavioural mode 2 this was opposite meaning that the fan was turned on as the last control action when the occupant felt warm and was turned off as the first control action when the occupant felt cold. This meant that the fan was turned off more frequently as the control criteria narrowed in Behavioural mode 1. In Behavioural mode 2 the fan was turned on more frequently when the control criteria narrowed.

Circulation pump: In the behavioural mode 1 simulations, the heating was on for a longer period than in behavioural mode 2. This meant that the circulation pump was on for a longer period, which resulted in larger energy consumption in behavioural mode 1 than in behavioural mode 2.

Lighting: The differences in energy consumption for lighting are due to differences in daylight level. These differences were caused by differences in the use of blinds in the simulations.

CONCLUSIONS

Occupant behaviour affected the energy consumption in the building by up to 330 %. The behavioural mode affected the energy consumption in the room by up to 324 %, while the control criteria affected the energy consumption by up to 117 %.
All simulations with active occupant behaviour resulted in near neutral thermal sensation, compared to passive occupant behaviour.

The results of the study underline the importance of appropriate occupant behaviour for the consumption of energy to climatize buildings by quantifying the difference between a naïve and a rationally behaving occupant.

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